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NBS Corridor Fire Tests: Energy and Radiation Models

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NBS Corridor Fire Tests: Energy and Radiation Models

Francis C. W. Fung

Structures, Materials, and Life Safety Division

and

Miles R. Suchomel and Philip L. Oglesby

Fire Technology Division

Institute for Applied Technology
National Bureau of Standards
Washington, D.C. 20234

U.S. DEPARTMENT OF COMMERCE, Frederick B. Dent, *Secretary*
NATIONAL BUREAU OF STANDARDS, Richard W. Roberts, *Director*

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LIST OF SYMBOLS

A Area of burn room door or corridor exit window

A_1 Corridor ceiling surface

A_2 Corridor floor surface

A_i (2/3)A/n, portion of burn room door or exit window area associated with one pitot tube

α Thermal diffusivity

B Subscript for burn room

C Subscript for corridor

c Specific heat, or velocity calibration constant

$\mathring{I}_B, \mathring{I}_C$ Rate of change of total internal energy of the burn room or corridor

i Subscript i for pitot tube

δ Thermal layer in heat conduction calculations

K Thermal conductivity of solids

K_g Thermal conductivity of gases

$\mathring{L}_B, \mathring{L}_C$ Surface heat losses in burn room or corridor

$\ln$ Natural logarithm

N Number of cribs in burn room

n Number of pitot tubes above neutral plane and in direction of gas flow

Δp Dynamic pressure

ϕ_1, ϕ_2 Angles in radiation calculation

Q Heat release per unit mass by cribs

$\mathring{Q}_B$ Energy transfer from the burn room to the corridor by convection and radiation

$\mathring{Q}_C$ Energy transfer from the corridor to outside by convection and radiation

r Distance between dA_1, dA_2 in radiation calculation

$\mathring{R}_B, \mathring{R}_C$ Heat release rates due to combustibles in burn room or corridor

ρ Density of solids

$\overline{\rho c}$ Averaged volumetric heat capacity of gases

S Control surface area, or flame spread distance

σ Stefan-Boltzman constant

t Time

T Absolute temperature

T_F Carpet flame temperature

T_g Gas temperature

T_i Gas temperature at ith pitot station

T_O Averaged fuel bed temperature

T_p Carpet pyrolysis temperature

T_S Surface temperature

T_∞ Initial or ambient temperature

v Velocity

$\forall$ Control volume

V_F Carpet flame spread velocity

$\frac{dW}{dt}$ Measured rate of weight loss

x' Distance measured along the ceiling

x'' Distance measured along the floor

$\mathring{q}$ Heat loss per unit surface area

τ Thickness of carpet

X Distance along corridor floor

NBS CORRIDOR FIRE TESTS:

ENERGY AND RADIATION MODELS*

Francis C. W. Fung, Miles R. Suchomel**, and Philip L. Oglesby

The NBS corridor fire program is a continuing program to investigate the growth and spread of fire and smoke through a corridor when fire is initiated in an adjoining room. Due to recent fires involving floor coverings [1], and controversies over current floor covering flammability test methods, floor coverings have received special attention during the first phase of the corridor fire program. Results of the NBS program on corridor fires are presented under the unifying concepts of energy and radiation models. The major findings are:

1. One type of carpet fire hazard has been identified as the rapid flame spread over pile surface.

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2. The dominant mechanism that causes this flame spread is energy transfer from ceiling radiation. This is substantiated by measurements and calculations.
3. Carpet evaluation by critical cumulative energy input into the corridor has been found to be feasible and informative in terms of heat transfer mechanisms.
4. Finally, a radiant panel test appears to be a promising approach to simulate the corridor environment for second generation flooring tests.

Key words: Ceiling radiation; corridor fires: critical energy input; flame spread, calculation, and observations; floor covering evaluations; heat balances; heat transfer mechanisms; models, energy balance, radiation, and scaling.

1. Introduction

The NBS corridor fire program is a continuing program to investigate the growth and spread of fire and smoke through a corridor when fire is initiated in an adjoining room. The program is designed to study the effects of configuration, fuel loading, surface linings, ventilation, and other design parameters on the spread of fire through corridors in multiple occupancy buildings. Due to recent fires involving floor coverings [1][1], and controversies over current floor covering flammability test methods, floor coverings have received special attention during the first phase of the corridor fire program.

In a preceding paper [2], presented as an introduction, the NBS corridor fire program was discussed in the light of available literature on corridor fires with regard to objectives, facilities, and approaches. In addition, qualitative discussions on effects of forced air draft, and carpet with and without pad on corridor fire spread were also presented.

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[1] Figures in brackets indicate the literature references at the end of this paper.

Results of the most recent corridor fire experiements are presented in this report under the unifying concepts of energy and radiation models. Before proceeding to present our findings, it is necessary to review briefly the experimental program.

2. Experimental Facilities

The corridor facility used in the NBS program is shown in figure 1. The corridor is 30 feet long by 8 feet wide by 8 feet high, with provisions having been made to increase the width up to 12 feet and the height to 9 feet. The adjustable width and height will permit the examination of several aspect ratios. A doorway, measuring 6-1/2 feet high by 30-1/2 inches wide, located in the side wall at the near end of the corridor, connects the corridor to an 8 foot square by 9 foot high "burn room" where all the fires are initiated. Two 14 inch by 6-1/2 inch vents are located near the floor level on opposite walls of the burn room. Two access doors are located at the approximate center of the corridor length. An exit window, measuring 70-1/4 inches high by 41-1/2 inches wide, is located at the far end of the corridor.

The corridor is situated within a larger brick building, with only the exit window connected to the outside. Air

conditioning equipment provides air flow for material conditioning and for controlled draft whenever forced flow is desired. The unit is capable of supplying a maximum air flow of 7500 cfm at 75 °F, with the relative humidity at 30%. The basic construction of the corridor walls and ceiling is 5/8-inch thick, Type "X" gypsum boards, attached to a structure of metal studs, 16 inches on center. Between the studs are 2-inch thick fiber glass batts for insulation. A plywood or asbestos cement floor is placed over the brick floor when desired. The ceiling and flooring materials to be tested are then attached to the gypsum board ceiling and brick subfloor, respectively.

To develop the energy and radiation models, the corridor is equipped with thermocouples, pitot tubes, radiometers and heat flux meters to study the corridor fires as a function of air flow and heat transfer by radiation, convection, and conduction.

Measurements were made of temperature, velocity, total and radiant heat flux, weight loss of burning combustibles, smoke density, continuous gas analysis and batch gas sampling. Also 16 mm color motion picture coverage was provided by both a stationary camera and a roving camera. Specific sensor locations in the corridor and burn room are shown in figures 2 and 3. In all, approximately 100

channels of data are recorded by high-speed data acquisition equipment.

3. General Description of Experiments

In all the experiments reported, the corridor walls were lined with gypsum board and the corridor cross section was 8 feet by 8 feet. A typical experiment is initiated by igniting four wood cribs, each weighing approximately 43-45 pounds, in the burn room. This yields a fire loading of 2.7 lb/ft^2 of burn room floor area. The cribs were dried to a moisture content of approximately 10 per cent before each test. (In Tests 331 and 332 crib moisture measured 23% and 15% respectively. Energy release rates from cribs for these tests were found to be significantly lower.) The center crib is located on a load cell platform so that the rate of burning can be measured and the rate of energy release can be calculated.

The corridor ceiling materials used were gypsum, fiber, and particle boards. The flooring materials used were brick, carpet, vinyl asbestos tile and varnished oak floor. Where flooring other than the brick was used an asbestos cement board subfloor, covered with the flooring material to be studied, extended 8 feet into the burn room. Table 1 summarizes the tests conducted, with the corridor material

linings and flame propagation observations listed. Table 2 describes the materials used.

Draft conditions in these tests were either by natural convection or a forced draft of approximately 100 fpm. The forced draft used is within the range of the air flow encountered in corridors serving as return air plenums in enclosed buildings.

4. Experimental Observations

While a variety of parameters have been tested in the program, only the experiments which have the necessary and sufficient data for analysis under the concepts of energy and radiation models are presented for discussion in this report. All of the experiments selected for these discussions will have the following standard conditions: ignition by four wood cribs; walls and ceiling of gypsum board; no forced draft; and floor covering as the test material in the corridor. Brick, a number of carpets, vinyl tile and red oak have been used as floor coverings in experiments to date. All of the carpets passed the pill test. A rubberized hair felt pad used in some of the experiments did not pass the pill test. It is important to note here that the current federal standard does not require pads to pass the pill test.

The sequence of events in an experiment involving floor coverings usually follows the same pattern. After ignition, cribs would be burning vigorously at about 3 minutes sending hot gases and light smoke into the corridor along the ceiling. At about 4 to 5 minutes floor covering in the burn room should be ignited. Smoke and gases in the corridor would then greatly increase in intensity. If there were no floor coverings in the burn room, as in the case of reference run Test 339 with brick floor, the crib burning rate would reach a maximum at 7 minutes and stay at approximately that level until 14 minutes at which time the crib fire would begin diminishing (figure 4). During the period of maximum crib burning rate, the fire plume would extend from the burn room and lick the corridor ceiling near the burn room doorway while light smoke continued to pour out from the corridor. The air temperature at the burn room doorway for the reference run are within about 200 °C of the ASTM E-119 time-temperature history (figure 5).

When there are carpets in the burn room and the corridor, the wood crib burning rate invariably has a higher initial rate of climb and the burn room top doorway air temperature generally climbs slightly faster than the ASTM E-119 curve (figures 6, 7, 8, 9, and 10). The air supply to the burn room is through the small vents in the burn room, and through the burn room doorway. An interesting phenomenon

associated with carpet in the burn room is that the wood crib burning rate invariably takes a sudden drop (figure 4) indicating oxygen depletion in the burn room prior to flame spread in the corridor. This is believed to be due to the large volume of pyrolysis gases given off by the carpets, resulting in a fuel rich atmosphere.

Table 3 compares the corridor gravimetric smoke data for a number of tests. Note the heavy smoke concentration for Tests 340, 341, and 342 and the drop in the respective burning rates in figure 4. Also note that Test 344 has low smoke concentration. In fact, the level of concentration is of an order of magnitude lower than the other carpet tests, and very comparable to the reference test. If we go back to the burning rate plots (figure 4), we find that Test 344 and the reference test are the only two tests where the crib burning was not affected by the choking or oxygen depletion phenomenon.

Shortly after the carpet ignited in the burn room a flame was observed to spread slowly over the carpet surface from the burn room door and then to accelerate. Then the whole corridor would "flame over" with flame following the entire surface of the carpet. The term "flame over" has been used to describe the observed rapid flame spread, since there is a preferred direction in the corridor fire to distinguish

it from the more general flashover phenomenon. Table 4 lists the flame over initiation time for various tests.

Note with the exception of two tests, flame over initiation times cluster around 4-1/2 to 7 minutes. Figure 11 illustrates the flame over phenomenon by plotting the carpet surface flame spread distances against time. After a relatively slow flame initiation period, during which time the first 5 feet of the carpets became involved, the carpet flame would sweep to the end of the corridor. The slow down of the flame spread over the last few feet can be explained as an end effect. In Test 342 the smoke concentration is so high, choking took place inside the corridor during flame over as shown by figure 11.

The flame over phenomenon was observed with all carpets studied, including a wool carpet, an aromatic polyamide, and other synthetics. However, quantitatively each carpet fire burned differently when considering energy and flame initiation rate. These and other findings will be discussed in more detail in the following sections.

Examination of the carpet and combustible pad after tests indicates that the rapid flame spread is strictly a surface phenomenon involving only the top pile of the carpet. However, if the fire is allowed to continue to burn then the

pad and the subfloor become involved, contributing additional smoke and fire.

Appendix A contains descriptive observations of significant events that took place in the corridor for Test 330 to Test 345. Test 331 and Test 332 were omitted because of high crib moisture content of 23% and 15% respectively.

5. Energy Balance Calculations

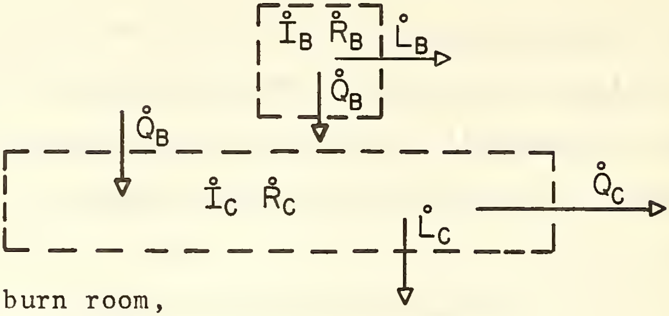
Due to the variation of the crib burning rates, caused by variations of the available oxygen, and due to the narrow spread of flame-over initiation times among some carpets, it is felt that carpet hazard evaluation by flame spread observation alone is not adequate.

A better definition of the hazard could be the ease with which the carpet will ignite and start to propagate a fire; and this brings us to the critical energy input concept. Before proceeding with the critical energy concept the energy balance calculation for the corridor system must be derived.

5.1 Energy Balance Equations

To perform the energy balance calculations it is necessary

to conceive separately a control volume enclosing the interior of the burn room, and a control volume enclosing the interior of the corridor as follows:



For the burn room,

$$\mathring{I}_B = \mathring{R}_B - \mathring{Q}_B - \mathring{L}_B, \text{ or} \tag{1}$$

$$\mathring{R}_B = \mathring{I}_B + \mathring{Q}_B + \mathring{L}_B \tag{2}$$

For the corridor,

$$\mathring{I}_C = \mathring{R}_C + \mathring{Q}_B - \mathring{Q}_C - \mathring{L}_C \tag{3}$$

$$\mathring{R}_C = \mathring{I}_C - \mathring{Q}_B + \mathring{Q}_C + \mathring{L}_C \tag{4}$$

where subscripts B, C indicate burn room and corridor respectively; and

$\mathring{R}_B, \mathring{R}_C$: heat release rates due to combustibles in burn room or corridor.

$\mathring{L}_B, \mathring{L}_C$: heat losses through surfaces of walls, ceiling, and floors by conduction.

$\mathring{Q}_B$: energy transfer from the burn room to corridor by convection and radiation.

$\dot{Q}_C$: energy transfer from the corridor to outside by convection and radiation.

$\dot{I}_B, \dot{I}_C$: rate ^f change of total internal energy of the burn room or corridor.

The following general expressions, valid for both burn room and the corridor, are used in the previous heat balance equations. To avoid repetition, subscripts B and C have been dropped in the following for more generality.

Rate of change of total internal energy is given by:

$$I = \forall\ \overline{\rho c}\ \frac{d\overline{T_g}}{dt} \tag{5}$$

where,

$\forall$ = volume of the control volume

$\overline{\rho c}$ = averaged volumetric heat capacity of gases in control volume

$\overline{T_g}$ = averaged gas temperature in control volume

$\frac{d}{dt}$ = derivative with respect to time

To calculate the convective and radiant energy heat transfer through doorway and exit window the following assumptions are made:

1. Both the velocity and temperature profiles can

be approximated by a finite number of linear segments.

2. For the range of velocities encountered kinetic energy of the gases can be neglected in the energy balance.

3. Temperature correction on velocity measurement behaves according to ideal gas law.

i.e. $$v = c\sqrt{\Delta p T} \tag{6}$$

where v = measured velocity

Δp = measured dynamic pressure

T = absolute temperature

c = velocity calibration constant

4. In radiation calculation blackbody emission will be assumed. This is considered a good approximation for the net-radiation from an enclosure fire [3]. Also no reradiation from the corridor to the burn room will be considered.

5. In convective energy transfer the neutral plane is taken to be at one-third of the height of the door or window.

With these assumptions we can write down the expression

for convective plus radiant energy transfer.

$$Q = \sum_{i=1}^{n} \rho_i c_i v_i (T_i - T_\infty) A_i + \sigma(\overline{T_g}^4 A - T_\infty^4 A) \tag{7}$$

where

A = area of burn room door or corridor exit window

n = number of pitot tubes above neutral plane and in direction of gas flow

ρ_i = density of gases at a particular pitot station

c_i = specific heat of gases at a particular pitot station (figures 2 and 3)

v_i = velocity of gas flow at a particular pitot station (figures 2 and 3)

T_i = temperature of gases at a particular pitot station (figures 2 and 3)

A_i = (2/3)A/n

σ = Stefan-Boltzman Constant

$\overline{T_g}$ = averaged gas temperature at door or window

T_∞ = initial temperature

The heat release rate of wood cribs is calculated from the measured weight loss data. Assuming that the burning rates of the cribs are not significantly different due to the rigorous interaction among cribs in the burn room, we can

write

$$\mathring{R}_B = NQ \frac{dW(t)}{dt} \tag{8}$$

where N = number of cribs in burn room

Q = heat release per unit mass for wood, 5000 Btu/lb [15]. This value is lower than bomb calorimeter data due to incomplete combustion.

$\frac{dW(t)}{dt}$ = measured rate of weight loss

The conductive heat loss is calculated by integrating heat loss per unit surface area over the entire control surface, for example:

$$\mathring{L} = \oint\!\!\oint \mathring{q} \, dS \tag{9}$$

where $\mathring{q}$ = the heat loss per unit surface

S = surface area of control volume

Applying integral method and assuming semi-infinite surfaces we obtain [4],

$$\mathring{q} = \frac{3K(T_S - T_\infty)}{\delta(t)} \qquad \text{and} \tag{10}$$

$$\delta(t) = \frac{4.9\sqrt{\alpha}\left[\int_0^t (T_S - T_\infty)^2 dt\right]^{\frac{1}{2}}}{(T_S - T_\infty)} \tag{11}$$

where K = thermal conductivity of solid

α = thermal diffusivity of solid

T_S = measured surface temperature

T_∞ = initial temperature

t = time

5.2 Results of Energy Balance Calculations

The previous expressions have been written into a Fortran program to handle routinely energy balance calculations for each test. The task of running the program is complicated by the fact that, due to the wide spread of temperature and velocity distributions spacewise and timewise throughout the history of a corridor fire, the accuracy of the heat balance is strongly dependent on the number of data points included. Examples of heat balance calculations shown in the following represent input data of approximately 100 channels at an interval of one-half minute per cycle.

Figures 12 to 16 present results of the burn room heat balance calculations. For each test as shown the instantaneous and cumulative values of as given by equation (8) are plotted and labeled as experimental "crib energy release" rate and cumulative curves, and the instantaneous and cumulative sum of all the terms at right hand of equation (2) are plotted and labeled as calculated "burn room cumulative

energy and rate balance" curves. Agreement of cumulative "crib energy release" and cumulative "burn room energy balance" curves are good for Tests 339, 343, and 344. For Tests 342 and 345 only partial load cell data were obtained. For the initial periods where load cell data was available, heat balance calculation and estimated energy release from load cell data agree in trend. In Test 342 the center crib fire went out after four minutes. Since the load cell was under the center crib and the estimated crib energy release was based on data from that load cell, it was necessary to terminate the crib energy calculation at approximately four minutes. In Test 345 the instantaneous and cumulative crib energy curves are also terminated at approximately four minutes; this time due to load cell malfunction.

A quick inspection of figures 12 to 16 shows that all the burn room instantaneous energy curves peak out at 60-80 x 10^3 Btu/minute between 4 and 6 minutes. For Tests 342, 343, and 345, the occurrence of early flame over invariably causes the burn room energy level to drop rapidly from this peak. This is due to the choking phenomenon discussed earlier. For Tests 339 and 344 where flame over either did not occur or occurred late, the burn room energy curves for both cases leveled off to a steady value of 60 x 10^3 Btu/minute. It is important to point out at this stage that the choking off of the burn room energy supply does not imply a lessening of

fire hazards. On the contrary it means that the picking up of activities in the corridor has added a new dimension to the fire. As will be shown later, measurements of energy and smoke output from the corridor indicates that when the burn room is being choked off maximum amounts of smoke and fire energy pour out from the corridor. Furthermore, tests where burn room fire choke off occurred also had a comparatively higher energy output from the corridor, indicating more intense fires. Due to the fair agreement of estimated energy release and calculated energy transfers in the burn room as shown by figures 12 to 16, it is felt that the techniques for evaluating energy input and output from the corridor as discussed in Section 5.1 yields results of acceptable accuracy for carpet evaluation.

Figures 17 to 20 compare the burn room heat loss by conduction through walls, ceiling, and floor to the total crib energy release rate. In all cases the burn room interior was sprayed with a one-inch thick protective coating of refractory material over basic masonry construction. This monocoat refractory coating has the following thermal properties:

Density	- ρ = 18.5 lb/ft^3
Thermal conductivity	- K = .057 Btu/hr ft °F
Specific heat capacity	- C = .2 Btu/lb °F
Thermal diffusivity	- α = .0015 ft^2/hr

With this refractory material as burn room interior coating it appears that the heat loss to the burn room surfaces by conduction is only of significant proportion during the early phase of the burn. For the remaining interval of the tests heat loss by conduction is roughly 15% of the total heat release. Thus the bulk of the energy released by the burning cribs is available as energy supply to the corridor in the forms of convective and radiant energy transport via the burn room doorway. Figures 21 to 25 compare the available energy to the corridor in the forms of convective and radiant energies. For all tests compared it appears that from an overall viewpoint the radiant contribution to the energy supply to the corridor is approximately 10% of the total energy transport into the corridor. This is because the corridor only sees the burn room fire through a small doorway. Thus apparently the corridor receives the bulk of the heat energy from the burn room in the form of convective heating. As discussed in previous sections and also illustrated by the velocity and temperature profile plots presented in Section 7, this available convective energy from the burn room is delivered to the corridor by way of a hot jet or stream along the corridor ceiling.

Figures 26 to 29 present the corridor energy comparison plots. In all cases the corridor walls and ceiling are

lined with 5/8-inch gypsum wallboards with fiber glass insulation backing. The thermal properties of gypsum board as used in heat loss calculation were as follows:

$\rho = 60 \text{ lb/ft}^3$

$c = .26 \text{ Btu/lb °F}$

$\alpha = .008 \text{ ft}^2\text{/hr}$

$K = .125 \text{ Btu/hr ft °F} \qquad 0 \leq T \leq 200 \text{ °F}$

$K = .075 \text{ Btu/hr ft °F} \qquad 200 \text{ °F} \leq T \leq 400 \text{ °F}$

$K = (.05 + T/16{,}000) \text{ Btu/hr ft °F} \qquad 400 \text{ °F} \leq T \leq 2000 \text{ °F}$

Thermal properties of carpets used in heat loss and later flame spread calculations are tabulated in table 5. It is interesting to study the fire history by following the corridor energy curves as shown in figures 26 to 29 in conjunction with the observational remarks for a specific test as presented in Appendix A. To facilitate this comparison the flame initiation and extinguishment times have been marked on figures 26 to 29. Heat balances of the corridor have not been attempted due to lack of precise information on endothermic reactions and heat release estimates of affected carpets. This is due to a lack of information on the rate of reaction as well as to the area of carpet affected by the fire.

However, the significance of carpet energy contribution is apparent when the corridor energy output curves are compared

with the energy input curves. In general, the following remarks can be made about the magnitude of the various energy levels in the corridor:

1. The peak level of corridor convective energy output due to the carpet fire as measured at the exit window, is typically between 80 and 100×10^3 Btu/min. This compares to 60 and 80×10^3 Btu/min of energy input into the corridor as measured at the burn room door.

   In other words, the corridor fires due to the carpets are comparatively more intense than the burn room crib fires during the flame over period. From the previous approximate range of fire intensities of energy outputs, it would appear that the carpet fires tested are typically 25 to 30% more intense than the burn room fire with a fire loading of 2.7 lb/ft^2 of wood cribs.

2. The interactions between the corridor and burn room fires are very well illustrated by figures 26 to 29. During the height of a corridor carpet fire the burn room fire was invariably choked off. Although not shown in the figures in a less severe and slow fire, for example,

vinyl sheet or tiles, the burn room fire was not choked off.

3. The heat loss through corridor walls and ceiling by conduction during the preheating and flame initiation periods is sensitive to the rate of energy input into the corridor. In general, heat loss by conduction is approximately 15% of energy input. During flame over when the energy release in the corridor itself surges suddenly the heat absorption by the corridor accelerates and reaches significant proportions; during such times the corridor energy output also surpasses the energy input.

6. Floor Covering Evaluation by Energy Considerations

As mentioned earlier due to the variability of crib burning rate, the narrow spread of carpet "flame over" time as well as the "flame over" initiation time, it is felt that carpet evaluation by flame spread observation alone does not seem to be satisfactory. Furthermore, the flame spread phenomenon as observed in the full size corridor program and the model duct fire experiments conducted at NBS tend to be bimodal in nature [5]. The flame either flashed over rapidly or the flame did not propagate steadily at all.

In other words, the nature of flame spread observation is either "go" or "no go". Looking for some logical way to rank carpets studied so far in the corridor program, energy input and output were the logical choices.

In figures 30 and 31 the cumulative convective energy inputs from the burn room into the corridor are plotted for various tests. Due to the corridor and burn room fire interaction discussed previously, the shape of the energy curves behaved differently indicating different burning behaviors. However, from physical considerations one expects that the cumulative magnitude of energy supply into the corridor should remain a controlling factor. Thus if one puts down on these energy curves the time when each carpet flame over was initiated, one finds that each carpet did flash at a different critical energy input. Thus by arranging the carpets according to decreasing critical energy to flame over corresponding to increasing fire hazard, a physically meaningful method of evaluating carpet hazard can be arrived at.

Table 6 tabulates the results of carpet evaluation by critical energy input concept. Some interesting observations are as follows:

1. Carpet ranking by the corridor critical energy concept suggests a similar ranking with the ASTM E-162 radiant panel test ranking. The

general trend is similar with an exception of the order of ranking for wool and brown acrylic carpets.

2. Carpet ranking by the chamber critical energy concept from model duct tests developed by Denyes and Quintiere [5] ranks carpet in the same order as tests by the NBS rate of heat release calorimeter.

3. On close examination, an interesting observation is that the worst carpet on top table came out good on bottom tests, and the worst carpet by tests at bottom table came out rather good by the test in top table. The differences between the top and bottom groups of method of testing appears to be due to the roles played by ceiling radiation and carpet heat release. This will be further elaborated in Section 9.

4. In the next section, it will be shown quantitatively that this good agreement of the corridor test with the E-162 radiant panel test is not accidental but can be explained readily in terms of heat transfer mechanism.

5. Figure 32 presents comparison plots of corridor cumulative energy outputs as measured at the exit window. An interesting observation is that the worst performing carpets by critical energy input rankings also are the worst carpets in terms of energy outputs, despite the fact that the worst carpets also produced the largest quantities of smoke which tended to choke off the burn room fire. Note that all curves are terminated at the time near flame over.

7. Flame Spread and Ceiling Radiation

Figures 33 and 34 show some typical preheating gas temperature profiles prior to flame over inside the corridor, both as a function of height and at 10 feet and 20 feet from the burn room respectively. All temperature profiles shown exhibit the same vertical stratification as a result of the hot gases leaving the corridor along the ceiling and the cool air coming in from the far end of the corridor. The spread in the curves are mainly due to different flame over times in the various tests. The next three figures, figures 35, 36, and 37, illustrate this natural convection pattern very well. Figure 35 shows composite temperature and velocity profile plots for

a test where no flame over took place. Figure 36 shows the same type of profiles for a test where flame over did occur at 11 minutes. Figure 37 shows typical sequential temperature profile plots at the 20 foot station of the corridor illustrating the flame over phenomenon. We see that the vertical temperature stratification persisted during the entire preheating period, due to the cooling draft along the floor, the air temperature immediately above the floor surface is lower than the floor surface temperature as shown in figures 38, 39, and 40. This indicates that the floor is actually heated by exposure to ceiling radiation and cooled by convection inside a corridor. In other words, ceiling radiation plays an important role in preheating the corridor floor in a fire.

A study of the corridor ceiling surface temperature history as shown by figures 41 and 42 clearly indicates the intensity of ceiling radiation. In order to demonstrate that ceiling radiation is indeed important in carpet flame spread we performed the following radiation and flame spread calculations.

Consider an elemental area, dA_1 on the ceiling with temperature $T_1(x',t)$ as illustrated by figure 43, we shall assume that the ceiling temperature is uniform across the width but not along the length and the emmissivity of ceiling is close

to that of a blackbody. The incident heat flux at the point dA_2 located at X'' and at a given time t due to the entire ceiling is given by:

$$\mathring{q}(x'',t) = \iint_{A_1} \frac{\sigma T_1^4}{\pi} \frac{\cos \phi_1 \cos \phi_2}{r^2} \, dA_1 \tag{12}$$

where $\mathring{q}(x'',t)$ = incident radiation at   and time t

σ = Stefan-Boltzman Constant

r = position radius from dA_2 to dA_1

ϕ_1, ϕ_2 = angles shown in figure 43

Note that $\mathring{q}(x'',t)$ is a function of both time and location on the floor. For a given X'' and t, the above integration is performed for a finite number of segments on the ceiling. Given the measured experimental ceiling temperature data a numerical program [5] is written to repeat the above basic calculation to obtain the incident radiation on the carpet for a finite number of time intervals and a specific number of stations along the floor. Incident radiation calculated by this crude model agrees surprisingly well with measurements made by Gardon type radiometers as shown by figures 44, 45, and 46. In figure 47 some interesting calculated incident radiation comparison plots are presented for a number of flooring tests. The curves are radiation versus distance along the floor for different tests just prior to flame over. Note that the curves follow the same general trend, the difference in magnitude is primarily

due to different carpets flashing at different times. If one would use results shown in figure 47 to rank carpet according to its incident threshold radiation leading to flame over, one would find this ranking agrees with the rankings by critical cumulative energy input concepts. Presumably, a laboratory test for evaluating flooring materials should simulate a radiant distribution of this type along the specimen.

Integrating the threshold ceiling radiation curves shown on figure 47 along the corridor length and then dividing by the length we obtain as averaged threshold ceiling radiations 0.21, 0.39, 0.47, and .58 watt/cm^2 for Tests 342, 340, 333, and 344 in that order. This ranks carpets in the same order as by the corridor critical energy input concept shown in table 6.

To further illustrate the dominant nature of ceiling radiation in causing carpet flame spread, a simple flame spread calculation was performed by assuming that flame spread is governed by a simple flame spread formula given by [6 and 7]:

$$v_F = \frac{K_g}{\rho c \tau} \frac{(T_F - T_P)}{(T_F - T_P)} \tag{13}$$

where v_F = surface flame spread velocity

K_g = thermal conductivity of gas phase

ρ, C, τ = density, specific heat and thickness of carpet

T_F = flame temperature

T_P = carpet pyrolysis temperature

T_O = average fuel bed temperature

Note that both the carpet thermal properties and the carpet pyrolysis properties are involved. This formula has been advanced both by Parker [6] and deRis [7] in their diffusion flame theories, and has been successfully applied to correlate experimental observations by a number of authors. In the present application only correlation with flame-over initiation time will be considered.

For a thin fuel bed model T_o is assumed to be governed by:

$$\rho c \tau \frac{dT_0(x,t)}{dt} = \mathring{q}(x,t) \text{ , x is along corridor floor,} \quad t=0, \; T_0 = T_\infty \tag{14}$$

where $\mathring{q}(x,t)$ is the incident radiation on the floor calculated from the radiation program. For a thick fuel bed model T_o is assumed to be given by: [Appendix B]

$$T(x,t) = \frac{1}{2\sqrt{3}\,K} \left[\alpha \mathring{q} \int_0^t \mathring{q} \, dt \right]^{\frac{1}{2}} \tag{15}$$

where K, α are the carpet thermal conductivity and diffusivity, respectively. Note the difference between the thick

and thin fuel bed formulae. In the thick fuel bed model T_o is calculated by assuming the fuel bed as a semi-infinite solid and for any given time by integrating the temperature profile across the "thermal layer." Thus both the thermal conductivity and diffusivity of the carpet are involved and the thick fuel bed model has a time constant proportional to $\sqrt{\alpha t}$.

This simple flame spread model is then programmed numerically with time varying incident heat flux calculated from the previous radiation program and with carpet thermal properties measured by Suchomel and Kashiwagi (table 5) and carpet pyrolysis data input from McCarter [8]. Table 5 also lists the carpet pyrolysis and flame temperatures used, and their definitions. Details of the flame spread numerical program are presented in Appendix B. Flame spread time prediction from this numerical program checks fairly well with experimental observation with a ±20% difference. This result is tabulated on table 7. In general it seems that the thick fuel bed model yields better results. In these calculations the flame spread time is obtained by considering the first 5 feet of corridor as a critical region. Similar results would be obtained if regions further down the corridor were considered.

As a result of this flame spread calculation one can see that

ceiling radiation can cause the kind of carpet flame spread that was observed in the full scale corridor. So it is not surprising that the E-162 radiant panel test ranks carpets in good agreement with the full scale corridor test. It would thus seem that to simulate the corridor environment for a carpet test a radiant panel type test would serve the purpose well.

8. Conclusions

The following conclusions summarize the results obtained thus far in the NBS corridor fire program:

1. As a result of studies of the involvement of floor coverings in corridor fires we have identified the primary flooring fire hazard as the rapid flame spread over the pile surface [10].

2. Results of heat balance studies in the burn room indicate that the bulk of the heat released from burning cribs is channeled into the corridor in the form of convective energy. Energy transfer by radiation through the burn room doorway is of much lower proportion, typically only one-tenth of the convec-

tive energy transfer. Transient heat loss by conduction through walls is also found to play a somewhat minor role when compared to the energy transfer by ceiling jet and is only 20% of the total energy released by the burning cribs in the burn room.

3. Instantaneous convective energy measurements indicate that during corridor flame over, the maximum convective energy output from the carpet burning in the corridor exceeds the maximum burn room convective energy output by 25 to 30%. The fire loading due to the carpet alone, as measured by carpet density, is significantly lower than the 2.7 lb psf wood crib fire loading in the burn room. This illustrates the severity of the carpet flame over hazard.

4. Carpet evaluation by cumulative energy output is found to be not only feasible but also informative in terms of heat transfer mechanisms.

5. Both temperature and velocity measurements indicate that radiation rather than convection is the dominant heat transfer mode that causes

carpet flame over in the corridor. This is further substantiated by a flame spread calculation that predicts the observed corridor carpet flame over phenomenon when the corridor ceiling radiation is considered as the only heat transfer mode.

6. Both calculated and measured carpet surface incident radiation suggest that to simulate the corridor environment for a flooring test a radiant panel type test appears to be promising.

9. Future Work

The conclusions presented in the previous section are arrived at from the series of full scale experiments. In order for the conclusions to be acceptable under a wider range of parameters it is felt that perhaps they need substantiation with other variables. Our experience in conducting the large scale studies indicates that the controlling phenomena that take place in building fire spread, for example, ceiling radiation and convection plume under the influence of floor interaction, warrants further study. An experimental program simulating corridor fires of varying intensity was conducted by Hinkley, et al [16]. As a result of the study useful experimental

measurements and empirical correlations were obtained to characterize the ceiling radiation and the horizontal deflection of a vertical fire plume. However, the corridor ceiling and floor interaction was held to a minimum by raising the gas flame vertically away from the floor and by leaving out the sidewalls of a corridor. It was demonstrated in this report that the horizontal deflection of a vertical fire plume by an incombustible ceiling dramatically increases the radiation to combustibles away from the fire. In a follow-up study [17] ceiling radiation and horizontal flame deflection were characterized for a number of combustible ceilings. Again the corridor ceiling and floor interaction was held to a minimum to avoid feed-back from the floor. The report shows that a combustible ceiling lining will cause an increase in the length of the horizontal flames and a more rapid increase in the intensity of downward radiation than an less combustible one. Differences between combustible ceiling linings are found to be in the rate of increase of downward radiation rather than in the length of the horizontal flames.

Recent publications in the fire research community indicate a degree of optimism in developing successful scale models [10]. Thus an attempt should be made to substantiate the large scale studies with reduced scale models. A reduced scale program not only is much more economical, it allows

more systematic study of the variable because of less set up time; and it is also more akin to laboratory scale test developments. In a proper scaling study there should exist four major ingredients as shown by a number of references [10 and 11]. The Grashoff number[1] must be sufficiently large so that the flow will be turbulent convection and the vertical thermal stratification is maintained. Consideration of energy balance requires that energy supply must scale as $H^{5/2}$, and consideration of momentum balance requires that velocity must scale as $H^{1/2}$, where H is the ceiling height. In addition heat loss through the walls must be scaled so that the characteristic time of the model and full scale be close. Effect of forced draft on surface heat loss remains to be investigated and may be critical to carpet surface flame spread. Forced cooling of the corridor interior surfaces during preheating considerably delayed flame spread in two identical corridor tests with and without forced draft.

Added fundamental studies need to be conducted to expand the concepts developed in this paper. For example, basic

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1 The Grashoff number is typically 10^{10} in the corridor experiments. Since Gr H^3, a 1 foot ceiling puts Gr down to 10^7. A quick check indicates that a preferably minimum ceiling height should be probably greater than 1 foot.

thermal property measurements, local heat transfer studies, and surface flame ignition analysis, etc. Kashiwagi [12] at NBS is currently conducting carpet basic thermal measurements. Parker [13] has also made heat release measurements. Currently Kashiwagi [10] is also studying radiation ignition of carpet and one dimensional surface flame spread. Information on local flame spread on a carpet as a function of carpet material and construction should prove to be very useful added information.

A series of small scale duct fire experiments have been conducted at the NBS [5] with the aim of studying some of the variables in a tunnel type test. Information has been obtained with regard to the effect of flame spread due to air draft, duct heights, energy input and types of carpets. As pointed out in Section 6 comparison of results indicate that differences exist between the corridor and the model duct. Results from the full scale corridor are in good agreement with the ASTM E-162 radiant panel tests whereas the model duct experiments are in agreement with heat release tests in ranking carpets. It has been demonstrated in Section 7 that corridor ceiling radiation is indeed the dominant heat transfer mechanism that causes flame over in the corridor. Thus convective and radiative heat transfer from the corridor carpet flame near the doorway appears to be secondary in the initial phase of corridor heat

build up. The agreement of the model duct experiments with heat release tests on the other hand points to the importance of carpet heat release in causing flame spread. The roles played by ceiling and carpet flame heat transfer during preheating have been discussed in Reference 5. It is important to point out that the degree of interaction between these two modes of heat transfer and the role each plays in flame spread is strongly dependent on the relative energy inputs. Thus in order to establish meaningful carpet fire hazard tests the relative importance of the aforementioned heat transfer modes and their synergistic effects must be studied and quantified. Initial attempts to study these interesting and complex phenomena has been initiated at NBS with a program [14] for studying a second generation radiant panel.

APPENDIX A

TEST OBSERVATIONS

Test 333, Brown Acrylic Carpet

Time Min:Sec	Remarks
00:00	140 grams heptane were placed beneath each crib.
00:02	Last crib ignited.
04:00	Cribs burning vigorously and flames reaching ceiling of burn room.
05:00	Carpets smoldering in center of burn room.
05:40	Carpet burning inside burn room.
06:00	Dense smoke in burn room.
06:15	Flaming reaching down to floor in corridor.
06:40	Smoke sample taken and sample of gas taken at 8 foot height.
07:15	Gas sample no. 2 taken at 7 foot height.
07:45	Fire on carpet in corridor.
09:24	Gas sample no. 3 taken at 4 foot height.
11:40	Flaming up the exit window.
11:40	Flaming out of window and igniting louvers.
11:55	Hose stream applied; dense smoke continues to come out in puffs.
12:10	Fire on floor increasing in intensity.
13:20	Hose stream applied for second time. Black smoke continuing to come out of window.

Time Min:Sec	Remarks
14:00	Flaming still coming out of burn room and touching ceiling.

It was observed after the test that the pad was smoldering. Doorknob of north exit was observed to have melted.

TEST OBSERVATIONS

Test 334, Brown Acrylic With Pad, Particle Board Ceiling, Forced Draft

Time Min:Sec	Remarks
00:40	Last crib ignited by torch ignition to tin cans.
02:00	Cribs burning moderately, flames about 3 feet high.
03:50	Smoke starting to build up.
04:15	Carpet beneath NW crib starting to burn.
05:30	Flames starting to progress down carpeting and coming out of the burn room.
06:00	Smoke sampling equipment started by Dr. Birky. Twenty-two foot and location 5 feet height.
06:35	Gas sample no. 2 taken at 7 foot height and 20 feet down corridor.
07:00	Gas sample no. 1 taken at 8 foot height and 20 feet down the corridor. Much smoke coming from corridor window.
07:50	Smoke continuing to come out of the burn room but some clearing because flood lights becoming visible.
09:00	End of smoke sampling.
09:20	Flames flashed over and coming out of corridor window.
09:35	Water on.
10:15	Ceiling starting to burn above burn room door; carpeting continuing to burn.
13:00	Extinguishment continuing.

Time Min:Sec	Remarks
18:00	Data logger shut down. Fire fighting efforts continuing.
	End of test

TEST OBSERVATIONS

Test 335, Varnished Oak

Time Min:Sec	Remarks
01:30	Flames on top of all cribs.
02:00	Flames 6 feet high.
02:45	Flames to ceiling.
03:15	Occasional flame licking out door.
03:45	Flames licking corridor ceiling.
04:45	Flames rolling down ~6 feet on ceiling.
05:00	Wood floor burning to middle of doorway.
05:30	Flames bending into burn room.
07:00	Left wall ignited, then right wall. Flames extend down wall approximately to 3 feet in height.
08:50	Flames out of exit window.

TEST OBSERVATIONS

Test 336, Vinyl Tile Floor

Time Min:Sec	Remarks
00:20	Doors closed. All cribs burning.
02:00	Light grey smoke in corridor.
03:00	Flames to ceiling of burn room.
04:00	Occasional light ash flying into corridor.
04:40	Flames out doorway.
05:00	Floor beginning to smoke in burn room. Flames licking corridor ceiling.
05:20	Corridor ceiling flames to 8 feet distance along corridor.
06:00	Heavy smoke, occasional sparks.
06:30	Flames on floor 1 foot out of doorway and advancing but bent toward fire room. Flames past observation under No. 2 on ceiling. Flames to 3 feet distance on corridor floor. Mainly along joints where tile cement vapors burning.
08:00	Flames two tiles (18") beyond E door edge on floor. Gypsum board burning on wall down to side doors.
09:00	Window No. 2 cracked.
13:00	Flames on floor at least to Window No. 2; bending toward fire room. Flames still emerging from burn room into corridor ceiling.

TEST OBSERVATIONS

Test 337
Sample No. 1--Rug, No Pad
Gypsum Board Walls & Ceiling 0 cfm Draft

Time Min:Sec	Remarks
00:16	Fourth crib ignited.
05:22	Flames coming out of burn room door.
06:00	Flaming in corridor air near burn room door. Gas sample no. 1 taken.
06:45	Gas sample no. 2 taken. Voluminous quantities of smoke out of window but no flaming.
24:36	Garden hose applied to cribs through burn room vents.
29:50	Data logger shut down. End of test.

Postmortem shows burning to 5 feet and singeing to 15 feet.

TEST OBSERVATIONS

Test 338
Brown Acrylic Carpet, No Pad, Particle Board Ceiling

Time Min:Sec	Remarks
00:15	Last crib ignited. Small recorders 2 seconds behind dictated remarks. Data logger 6 seconds behind dictated remarks.
04:45	Flames coming out of burn room door and hitting ceiling.
05:00	Floor in burn room starting to smoke and charring from one crib.
05:15	Carpet ignited to the burn room.
05:31	Burn room doorway in flames (on floor).
05:39	Flaming in corridor air.
09:30	Firemen entering side of burn room and applying garden hose.
13:55	Truck recording equipment shut down.
14:45	Data logger shut down. Carpet appears to have burned entire length of corridor.

TEST OBSERVATIONS

Test 339, Reference Run, Brick Floor

Time Min:Sec	Remarks
01:00	Dictation 5 seconds ahead of smaller recorders. Dictation time same as data logger time. Dictation time 3 seconds ahead of movie clock.
03:45	The flames of the two cribs nearest the door were higher than the flames of the two cribs further from the door.
05:20	Flames starting to come out of burn room door.
06:00	Some charring of gypsum board nearest the doorway (west wall).
08:25	Window opposite burn room door steaming up on inside and smoke starting to come through edges of window.
09:30	Gypsum paper thoroughly charred around burn room, but no flashover occurring.
10:15	Gas sample no. 1 taken at 8 feet height and 20 feet down corridor.
10:30	Light bulbs heard poping and flashing in corridor.
10:50	Flashing sound continuing to be heard from outside of corridor.
11:18	Gas sample no. 2 taken at 6 feet height and 20 feet down corridor.
11:45	Movies commenced to be taken from window of south wall looking into burn room.
12:20	Gas sample no. 3 taken at 4 feet height and 20 feet down corridor.

Time Min:Sec	Remarks
16:00	Minute hand of movie clock appears to be 1 minute faster than stop watch; i.e. movie clock shows 17:00.
18:45	Movie clock corrected.
22:20	Water applied from garden hose to side of burn room through vent hole in east wall.
25:45	Data logger shut down.

TEST OBSERVATIONS

Test No. 340, Blue Acrylic Carpet With Pad

Time Min:Sec	Remarks
02:00	Clock at continuous recording instruments 3 seconds behind dictation time.
03:00	Data logger 3 seconds behind dictation.
03:30	Movie clock coincides with dictation time.
04:30	Carpet ignited in burn room.
05:00	Flames on carpet reaching burn room doorway.
05:05	Flaming in corridor air outside of burn room.
05:27	Gas sample no. 1 taken at 8 feet height and 20 feet down corridor (bottle marked III). Flaming and smoke in corridor as seen through side window.
06:00	Gas sample no. 2 taken at 8 feet height and 20 feet down corridor.
06:30	Gas sample no. 3 taken at 7 feet height and 20 feet down corridor. Flaming in gas cloud at window.
07:05	Flames coming out of corridor window.
07:30	Initial extinguishment commencing from outside exhaust window.
09:04	Garden hose extinguishment commencing from side of burn room. This procedure observed to be unnecessary because cribs in burn room no longer burning. Wood was blackened but still intact.
11:50	Data logger shut down.

TEST OBSERVATIONS

Test 341
Wool Carpet w/Rubberized Pad; Gypsum Board Walls and Ceiling w/Intumescent Paint

Time Min:Sec	Remarks
00:20	Last of the four cribs ignited.
02:00	Movie clock 3 seconds behind dictation time.
04:15	Windows steaming up.
04:30	Condensation on observation windows dissipating.
06:02	Carpet ignited in burn room.
06:15	Fire on floor beyond burn room and much smoke.
07:34	Gas sample no. 1 taken at 8 feet height and 20 feet down corridor. Carpet fires out; flaming on edge of pad in burn room.
08:00	Carpet in burn room reignited.
08:25	Flaming on corridor floor spreading throughout corridor.
08:50	Gas sample no. 2 taken at 8 feet height and 20 feet down corridor.
09:11	Gas sample no. 3 taken at 7 feet height and 20 feet down corridor.
09:27	Gas sample no. 4 taken at 4 feet height and 20 feet down corridor. Flaming observed to have spread across carpet surface.
09:30	Flames out of window.
10:28	Garden hose extinguishment commencing into side of burn room.

Time Min:Sec	Remarks
12:00	Extinguishment of flames on carpet surface commencing from corridor access door.
13:54	Data logger shut down.

TEST OBSERVATIONS

Test 342
Gold Nylon With Integrated Rubber Pad

Time Min:Sec	Remarks
00:17	Last crib ignited.
01:00	Observation windows commenced to steam over.
03:00	Steaming clearing up.
03:50	Some black smoke appearing in corridor air.
04:30	Flaming in upper part of corridor air.
04:45	Carpet on fire. Gas sample no. 1
04:50	Flaming in corridor air.
05:00	Gas sample no. 2 taken.
05:22	Gas sample no. 3 taken.
05:38	Gas sample no. 4 taken.
06:21	Flames commencing to extend beyond corridor exhaust window.
08:10	Extinguishment commencing with 1-1/2 inch hose line into corridor from exhaust window.
10:15	Extinguishment commencing into side of burn room by means of garden hose. Cribs not burned down. Center crib already out.

TEST OBSERVATIONS

Test 343, Wool Carpet, No Pad

Time Min:Sec	Remarks
03:57	Sample no. 1 taken (gas) 8 feet.
04:30	Rug in burn room ignited. Flames bending inwards towards center of burn room.
04:43	Flaming in corridor air.
04:57	Gas sample no. 2 taken (8 feet).
05:00	Flaming on corridor floor.
05:07	Gas sample no. 3 (7 feet).
05:10	Light bulbs commencing to "pop" in corridor.
05:15	Black smoke in corridor.
05:27	Gas sample no. 4 taken (4 feet).
07:00	Burning of walls and rug.
07:45	Smoke clearing but cribs continuing to burn in burn room.
10:18	Extinguishment commencing from side of burn room by means of garden hose.

TEST OBSERVATIONS

Test 344, Aromatic Polyamide Carpet, No Pad

Time Min:Sec	Remarks
01:00	All cribs burning.
02:00	Light smoke in corridor.
03:00	Carpet burning in burn room.
05:00	Gypsum board burning and charring near burn room.
06:00	Light smoke inside corridor.
08:10	Carpet burning outside burn room to a distance of 2 to 3 feet.
10:10	Ceiling flame continues to lick vigorously opposite burn room.
10:45	Burning of gypsum paper and paint began to spread.
12:00	Flames at top of window (?) D.G.
12:45	Ceiling, wall gypsum board completely involved; beginning of decisive flashover.
14:40	Heavy smoke, flaming around exit window. Carpet burning up to a few feet from exit window. Extinguishment began.

TEST OBSERVATIONS

Test 345
Brown Wool Rug-No Pad-0 cfm--Intumescent Fire Retardant Paint on Gypsum Board Walls and Ceiling

Time Min:Sec	Remarks
02:45	Slight smoke build-up in corridor air.
03:45	Cribs burning intensely--no fire on carpet.
04:10	Flames starting to come out of top of burn room door.
04:20	Carpet in burn room starting to smolder.
04:25	Carpet in burn room ignited.
04:30	Intense flaming in burn room air.
04:42	Much light smoke in corridor.
04:45	Steam on corridor observation windows.
05:08	Gas sample no. 1 taken at 8 feet height and 20 feet down corridor.
06:20	Light bulbs popping in corridor.
06:30	Much gray smoke pouring out of corridor exhaust window.
06:45	Flaming observed in corridor air from outside exhaust.
06:55	Flaming observed through smoke near corridor ceiling. No flaming pouring out of exhaust window.
07:50	All flaming observed to be in air above carpeting.
07:55	Much flaming in corridor air. Smoke started to clear.
08:05	Carpet burning (in flames) in corridor.

Time Min:Sec	Remarks
08:10	Second gas sample taken.
08:20	Third gas sample taken.
08:30	Last gas sample taken.
09:15	Water applied to cribs in burn room through vents in burn room walls.
10:10	Flaming subsiding appreciably in corridor without applying water (except in burn room).
11:30	Wood that supported clock in corridor still burning. Extinguished with garden hose spray.
14:00	VIDAR recording equipment shut down.

APPENDIX B

FLAME SPREAD CALCULATIONS

B.1 Flame Spread Calculations

From reference [4] the temperature profile inside a semi-infinite solid with one face exposed to a time varying heat flux is given by

$$T(x,t) - T_\infty = \frac{\mathring{q}\delta}{3K}\left(1 - \frac{x}{\delta}\right)^3 \tag{B1}$$

where

$T(x,t)$ = the temperature distribution

T_∞ = initial temperature

$\mathring{q}$ = the external heat flux

K = thermal conductivity of the solid

x = the x coordinate

δ = the thermal layer and is given by

$$\delta = 2\sqrt{3}\left[\frac{\alpha}{\mathring{q}}\int_0^t \mathring{q}\, dt\right]^{\frac{1}{2}}$$

where α is the thermal diffusivity.

To obtain the average semi-infinite fuel bed temperature, let

$$T_0 = \frac{1}{\delta}\int_0^t T(x,t)\, dx \tag{B2}$$

substituting (B1) into (B2) and integrate one obtains equation (15) in the following form,

$$T_0(x,t) = \frac{1}{2\sqrt{3}\,K}\left[\alpha \mathring{q} \int_0^t \mathring{q}\ dt\right]^{\frac{1}{2}} + T_\infty \tag{B3}$$

Equations (13) and (14) and equations (13) and (15) from Section 7 can be solved simultaneously to obtain the flame spread velocity. Integrating the velocity one obtains the flame spread distance along the corridor. For thin fuel bed model an explicit expression for the flame spread distance can be obtained and is shown as follows,

$$S = \frac{K_g}{\mathring{q}}(T_F - T_P)\ \ln\left[\frac{T_P - T_\infty}{T_P - \frac{1}{\rho c \tau}\int_0^t \mathring{q}\ dt}\right] \tag{B4}$$

For the thick fuel bed model, equations (14) and (15) are combined and integrated numerically in the following Fortran program. Both equation (B4) and the numerical calculation for the thick fuel bed flame spread distance show that the flame spread distances will escalate and exhibit "flame over" behaviors.

B.2 Flame Spread Numerical Program

A Fortran program was written to implement the flame spread calculations. The program was broken down into five main divisions. The first division was data input of the thermal properties, radiation, heat flux, and various timing data.

The second part was an algorithm to linearly expand the radiation data into integer amounts of subdivisions in order to increase the resolution of the flame spread formulas. (This was necessary procedure in order to detect the rapid change in velocity when TO approached TV.)* The algorithms first computed the intercept and slope of a linear curve between two half minute interval input data. The half minute sampling interval was then reduced to correspond to the finer interval size. A time variable was then used in the linear equation to generate the expanded data.

Part 3 was the primary integration routines, which generated the integrated radiation flux (TQDOT), the thin fuel

---

*The alphabetical symbols used in this section refer to portions of the computer code.

temperature (TO) and the semi-infinite fuel bed temperature (TOSI). The integration algorithms were of the backward difference trapezoidal form, for example, integrated value between interval "j" "j-1" for the function F(j):

$$\mathrm{Int}(j) = \frac{(F(j) + F(j-1))\nabla j}{2}$$

Control parameters MAX1 and MAX2 were defined to determine the maximum time for TO and TOSI less or equal to TV, after which the flame spread formulas have no meaningful significance.

Part 4 and 5 were the final algorithms which computed the flame spread velocities (V1) and (V1SI), and the distances for thin bed and thin fuel bed models.

Table 7 is a summary of the flame spread calculations versus the observation burning times. The percentage is based relative to the observation "flame over" initiation time by:

$$\%\ \text{error} = \frac{(\text{calculated - burn time value})}{\text{burn time value}} \times 100\%$$

The mean percentage error for the tests evaluated in Table 7 is approximately 20%.

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James S. Steel, physicist, was responsible for the installation of the instrumentation and the data acquisition equipment.

William H. Bailey, supervisory technician, was in charge of erection and dismantling of the corridor structure.

Thomas F. Maher, Melvin E. Womble, and Richard H. Zile, engineering technicians, participated in the maintenance and calibration of instrumentations and erection and dismantling of the corridor structure.

J. Newton Breese, physical science aid, participated in the preparation of the graphs.

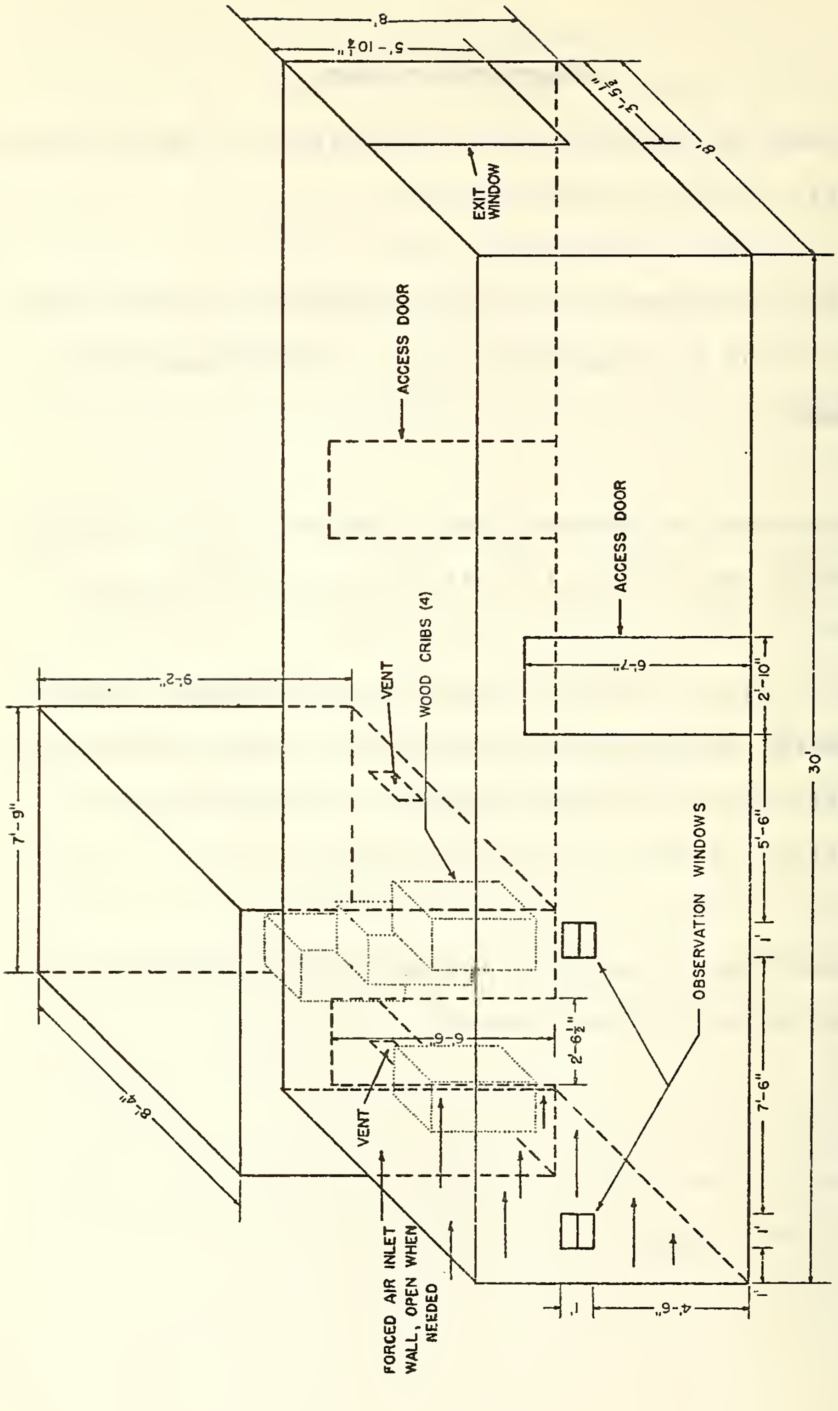

FIG. 1 CORRIDOR FACILITY

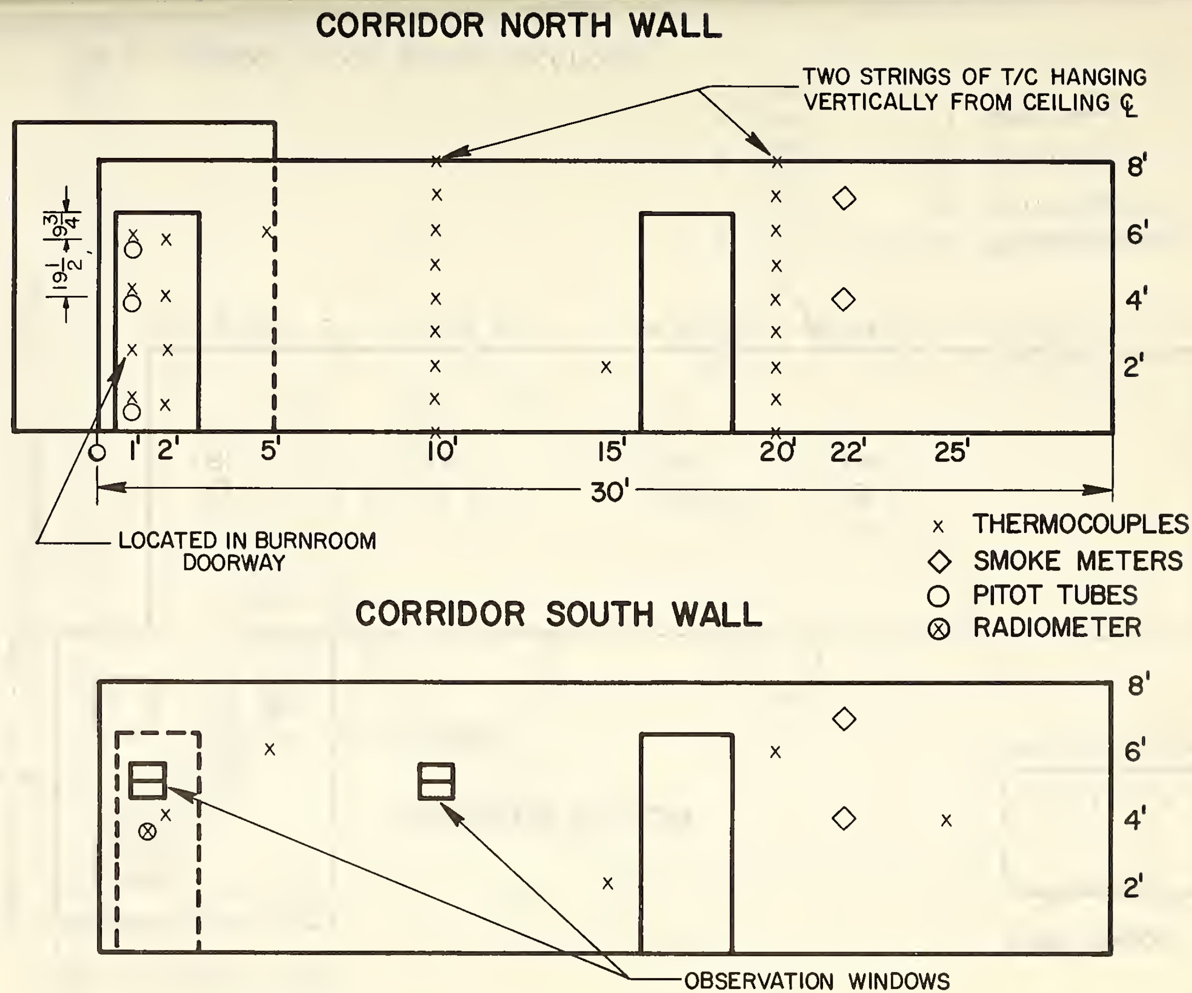

FIG. 2 CORRIDOR WALL SENSOR LOCATIONS

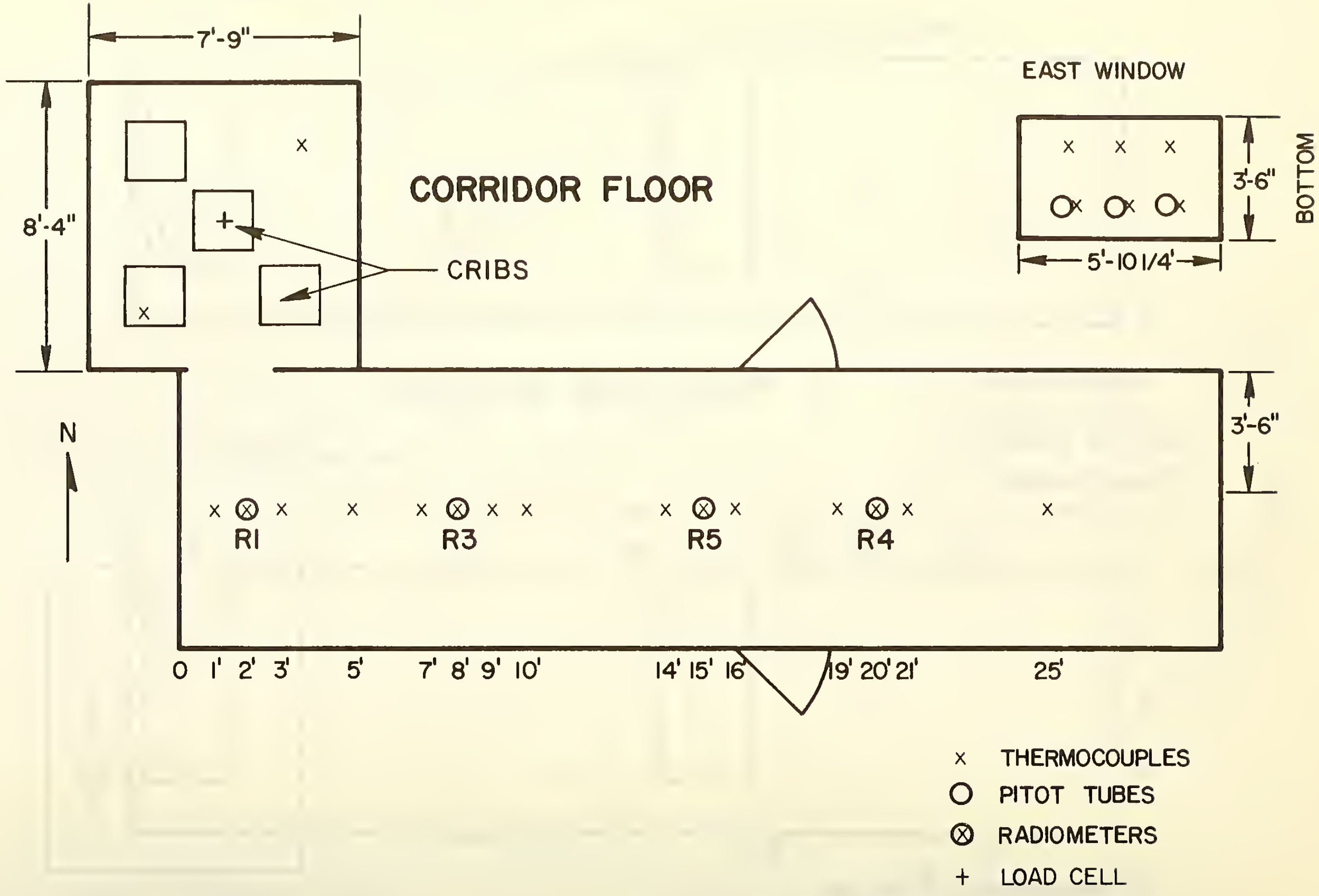

FIG. 3 CORRIDOR FLOOR SENSOR LOCATIONS

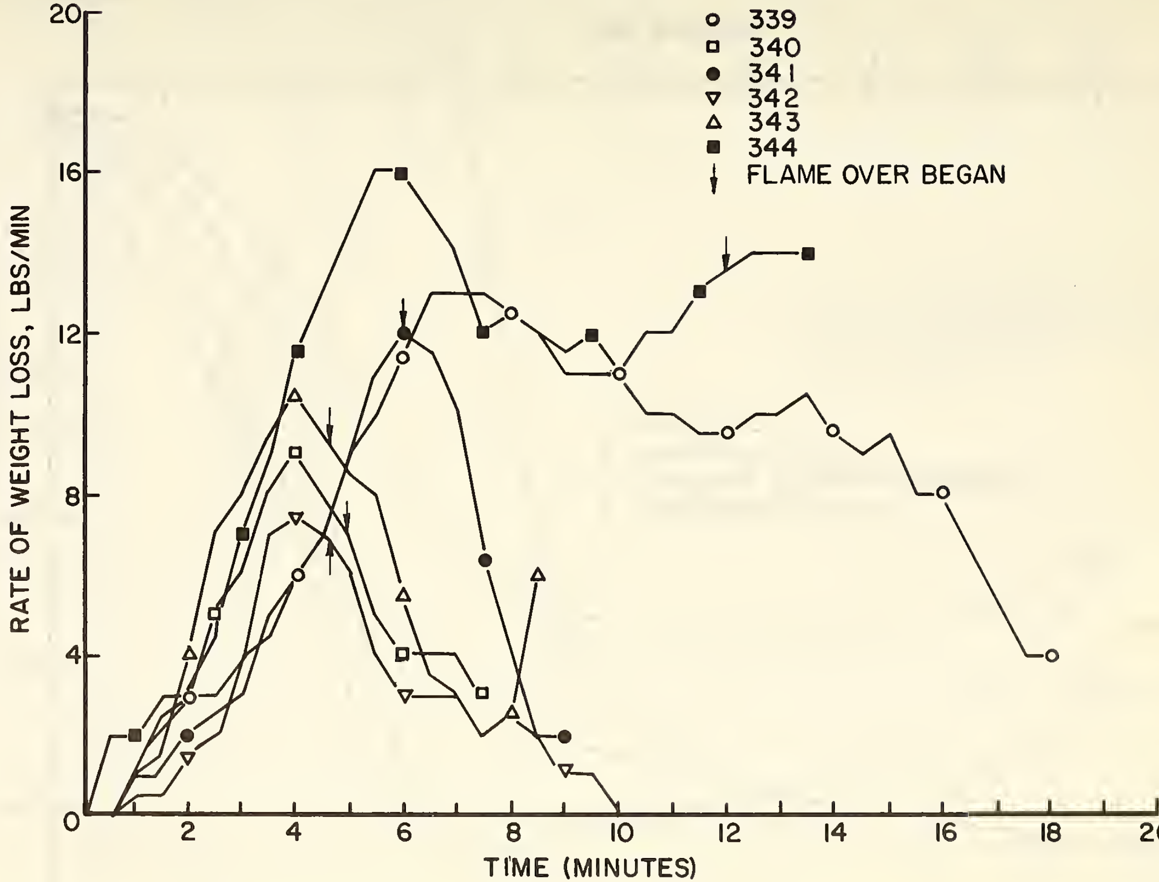

FIG. 4 TOTAL CRIB RATE OF WEIGHT LOSS

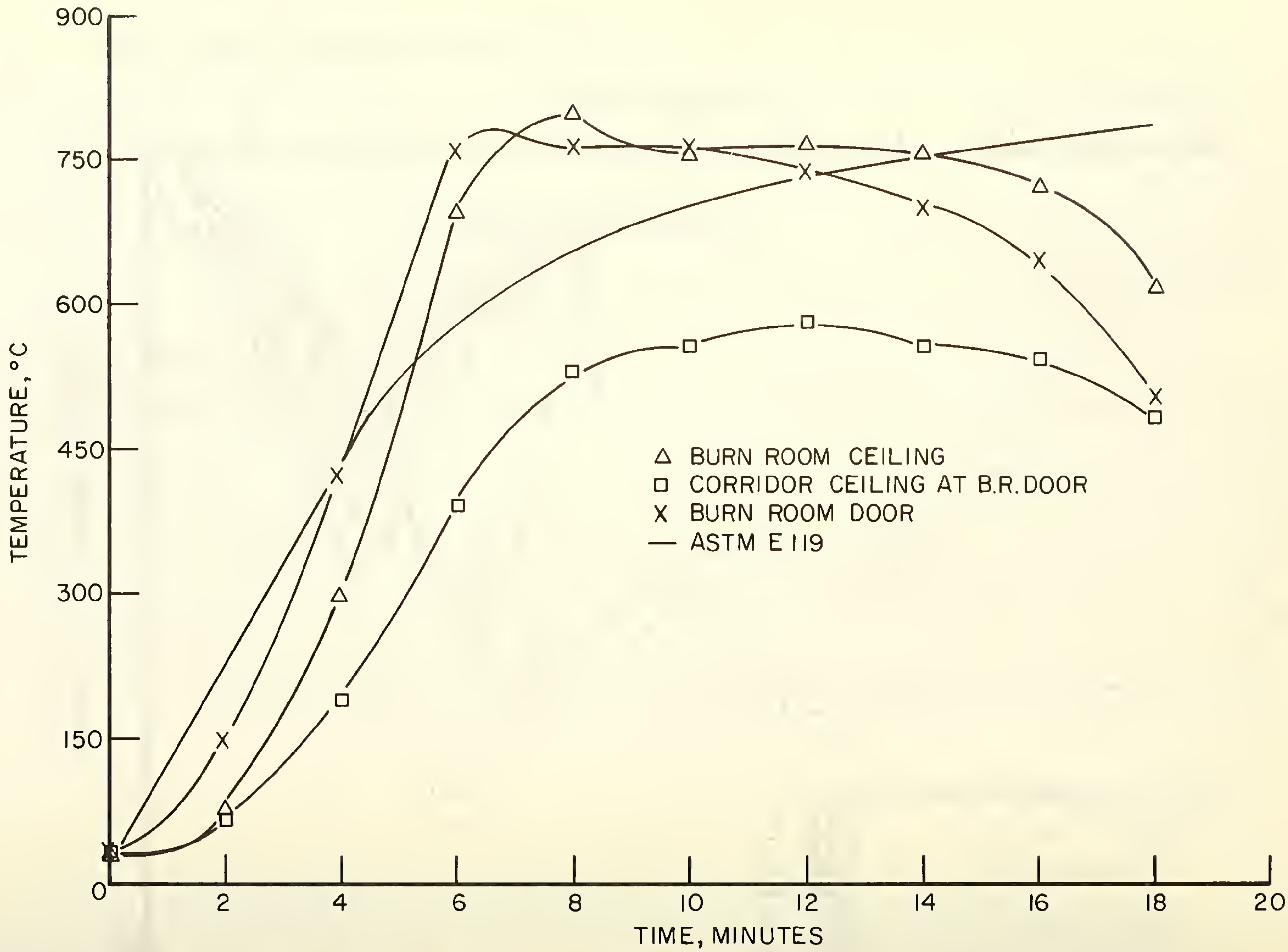

FIG. 5 TEMPERATURES NEAR CORRIDOR DOORWAY, TEST 339

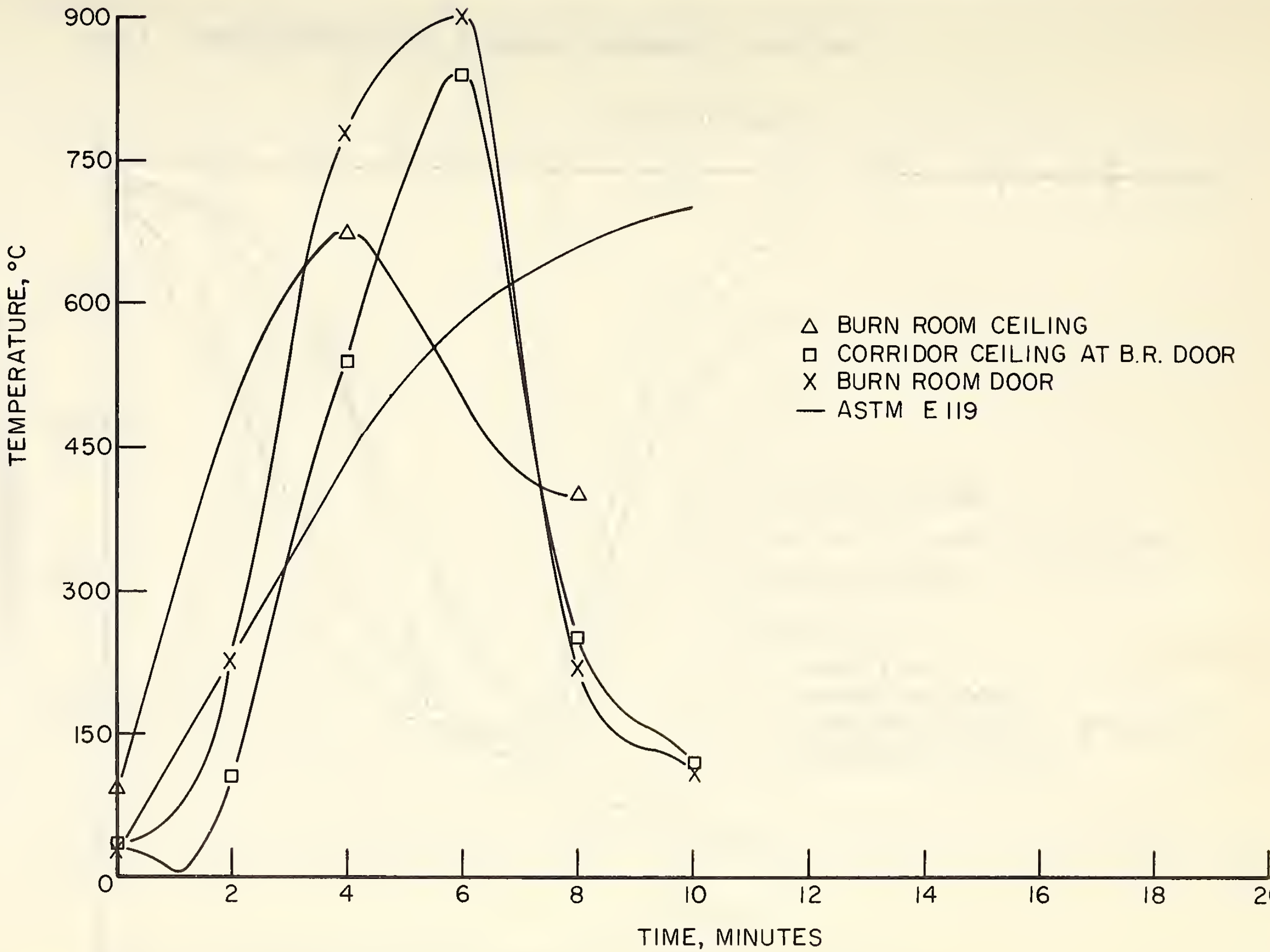

FIG. 6 TEMPERATURES NEAR CORRIDOR DOORWAY, TEST 340

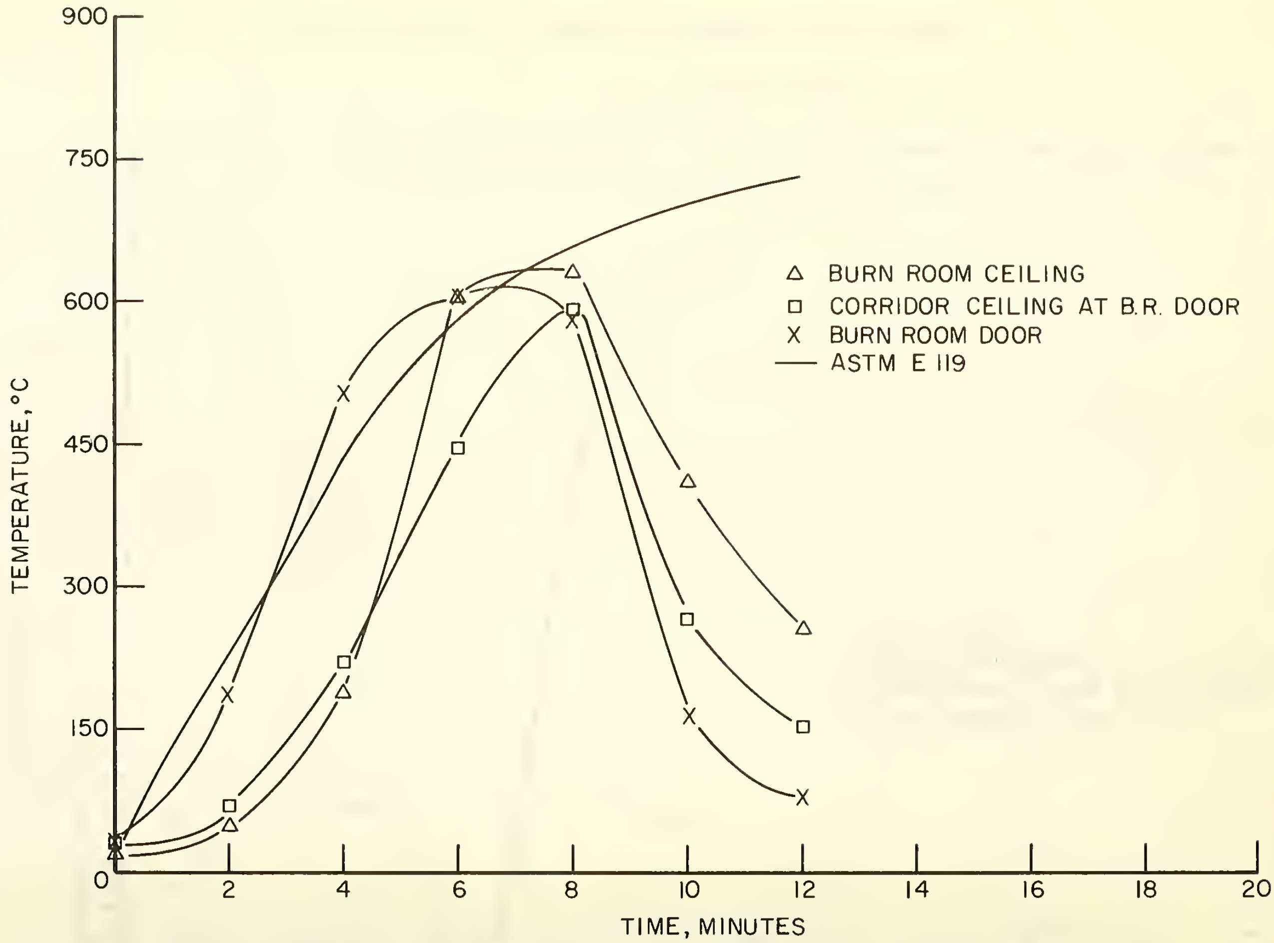

FIG. 7 TEMPERATURES NEAR CORRIDOR DOORWAY, TEST 341

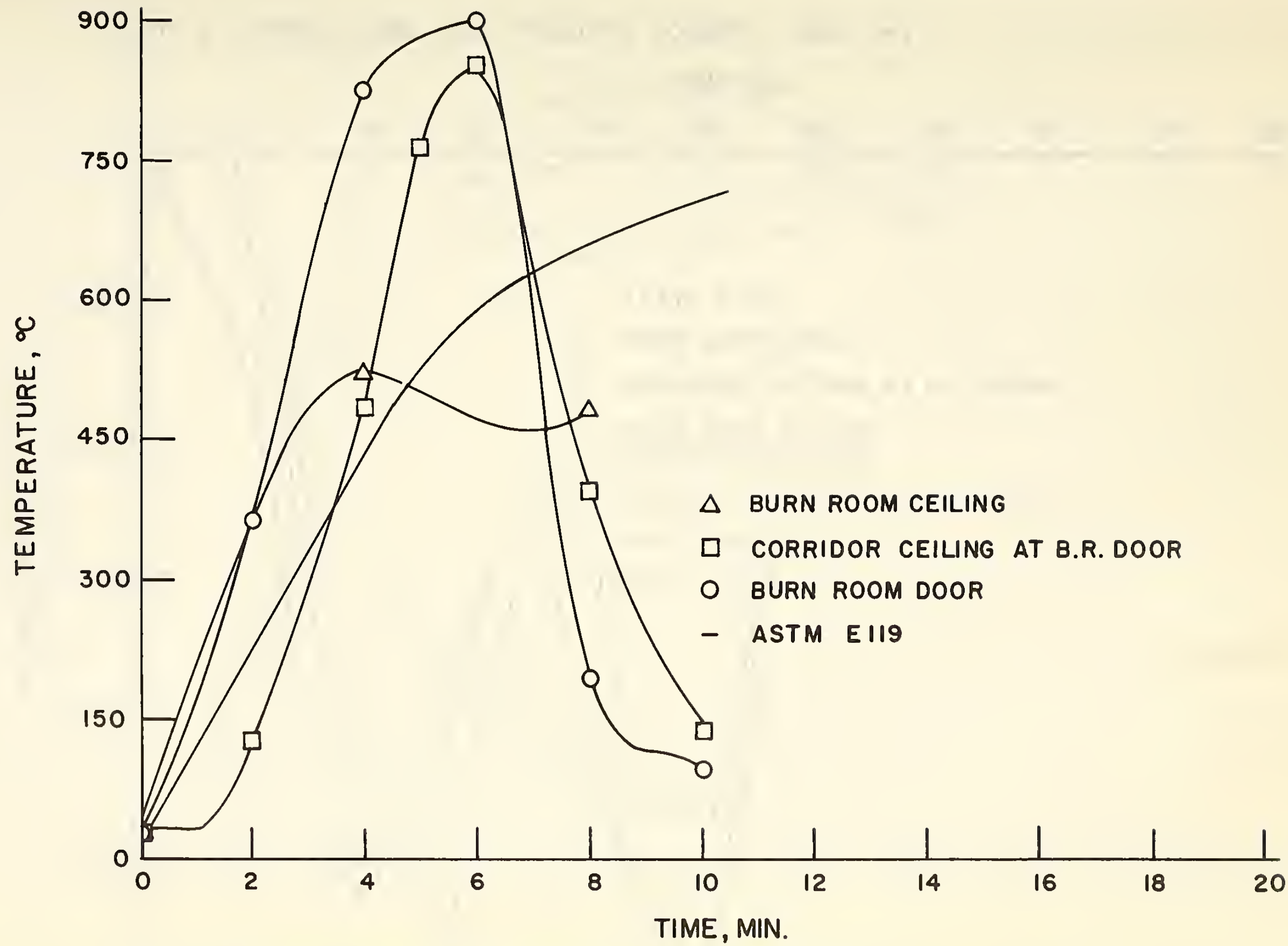

FIG. 8 TEMPERATURES NEAR CORRIDOR DOORWAY, TEST 342

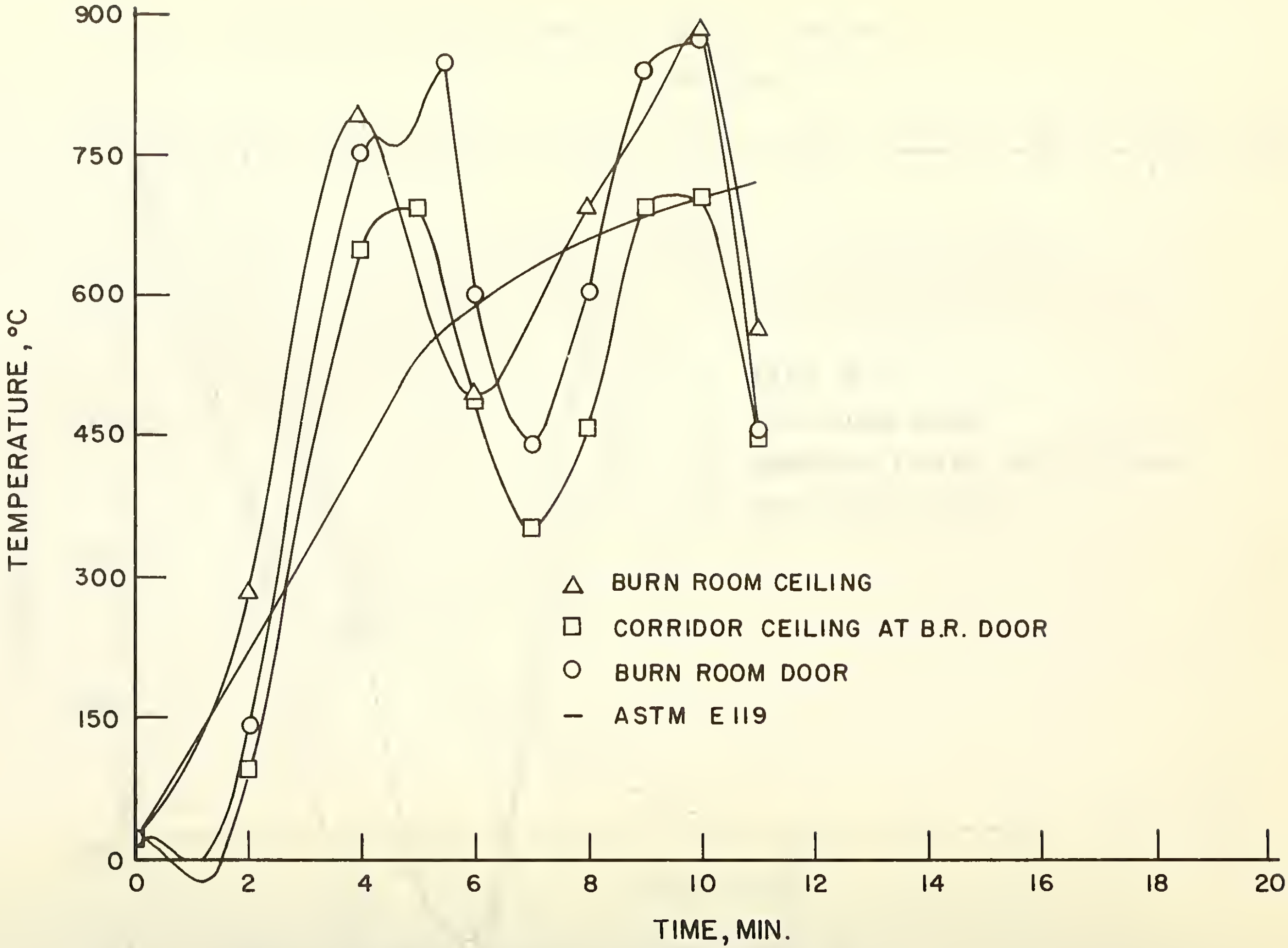

FIG. 9 TEMPERATURES NEAR CORRIDOR DOORWAY, TEST 343

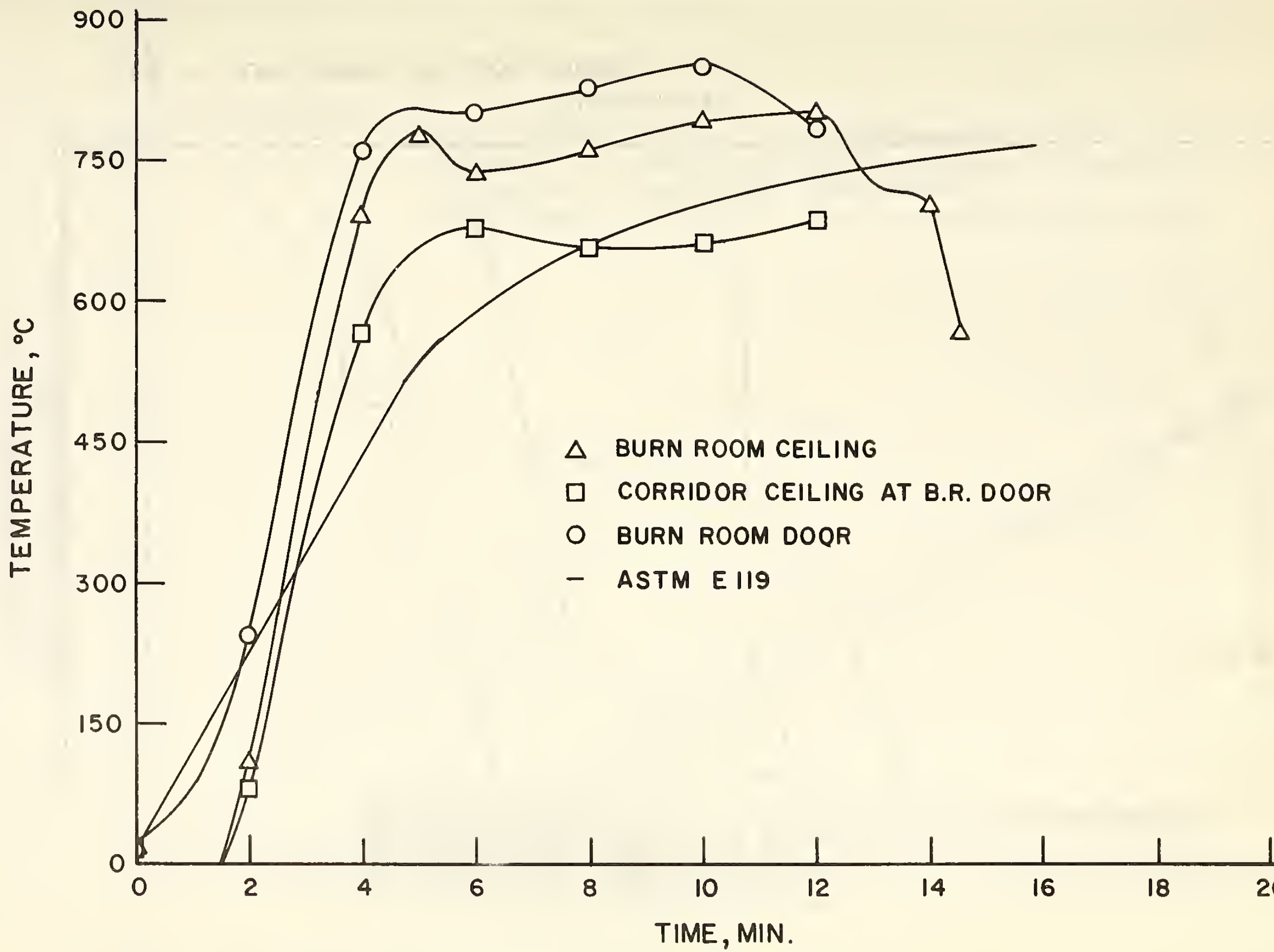

FIG. 10 TEMPERATURES NEAR CORRIDOR DOORWAY, TEST 344

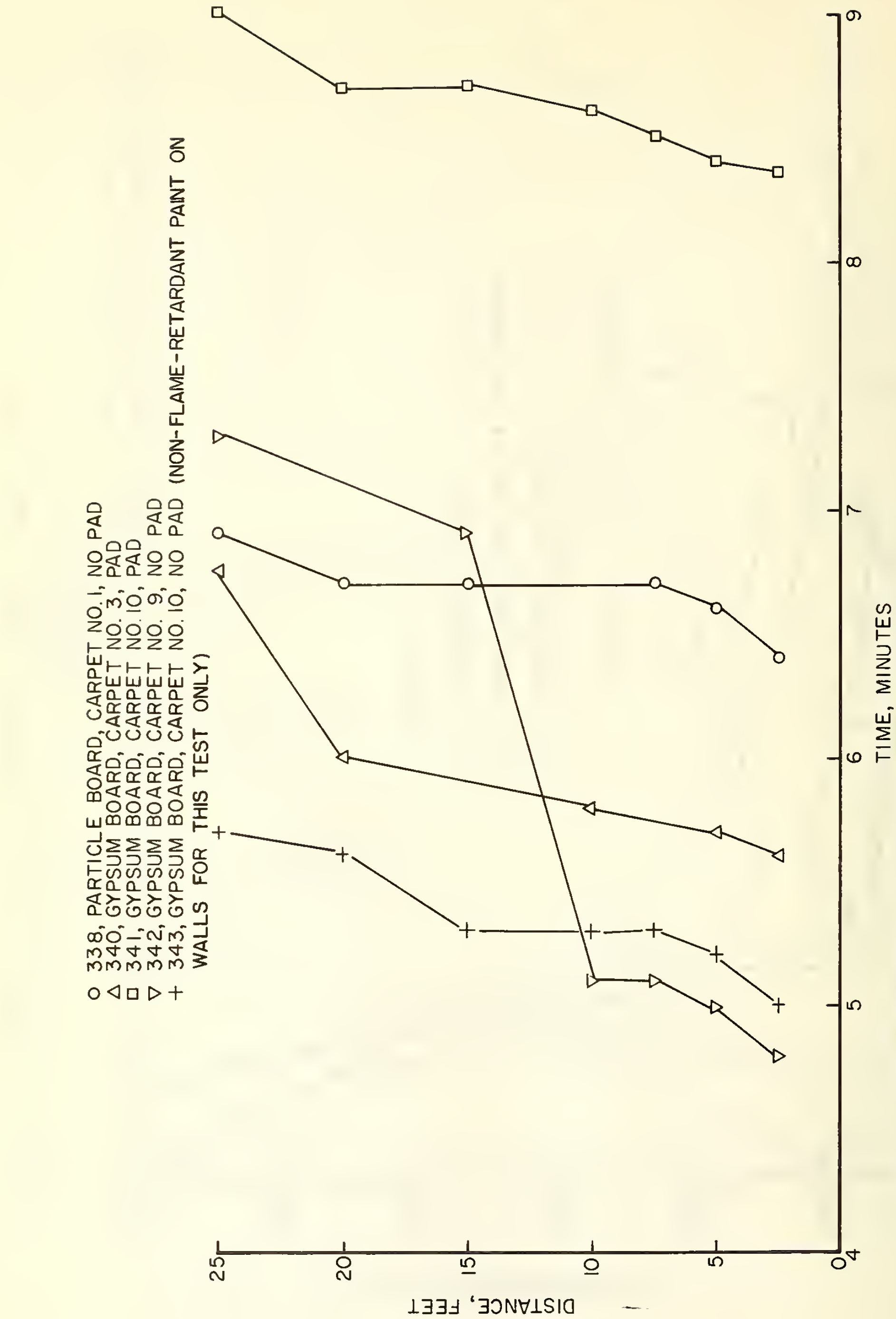

FIG. 11 FLAME SPREAD ON FLOOR COVERING

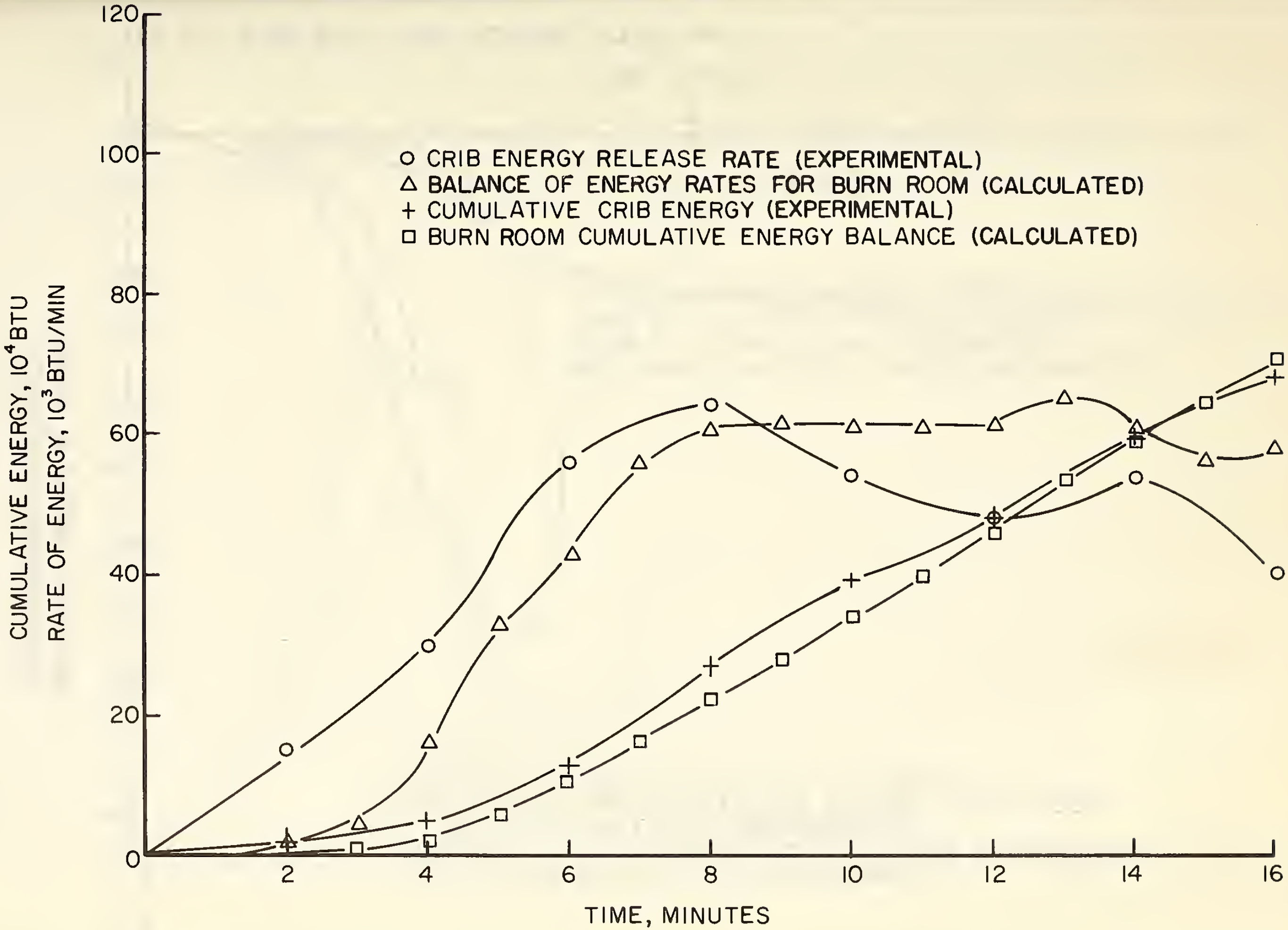

FIG. 12 BURN ROOM HEAT BALANCE, TEST 339

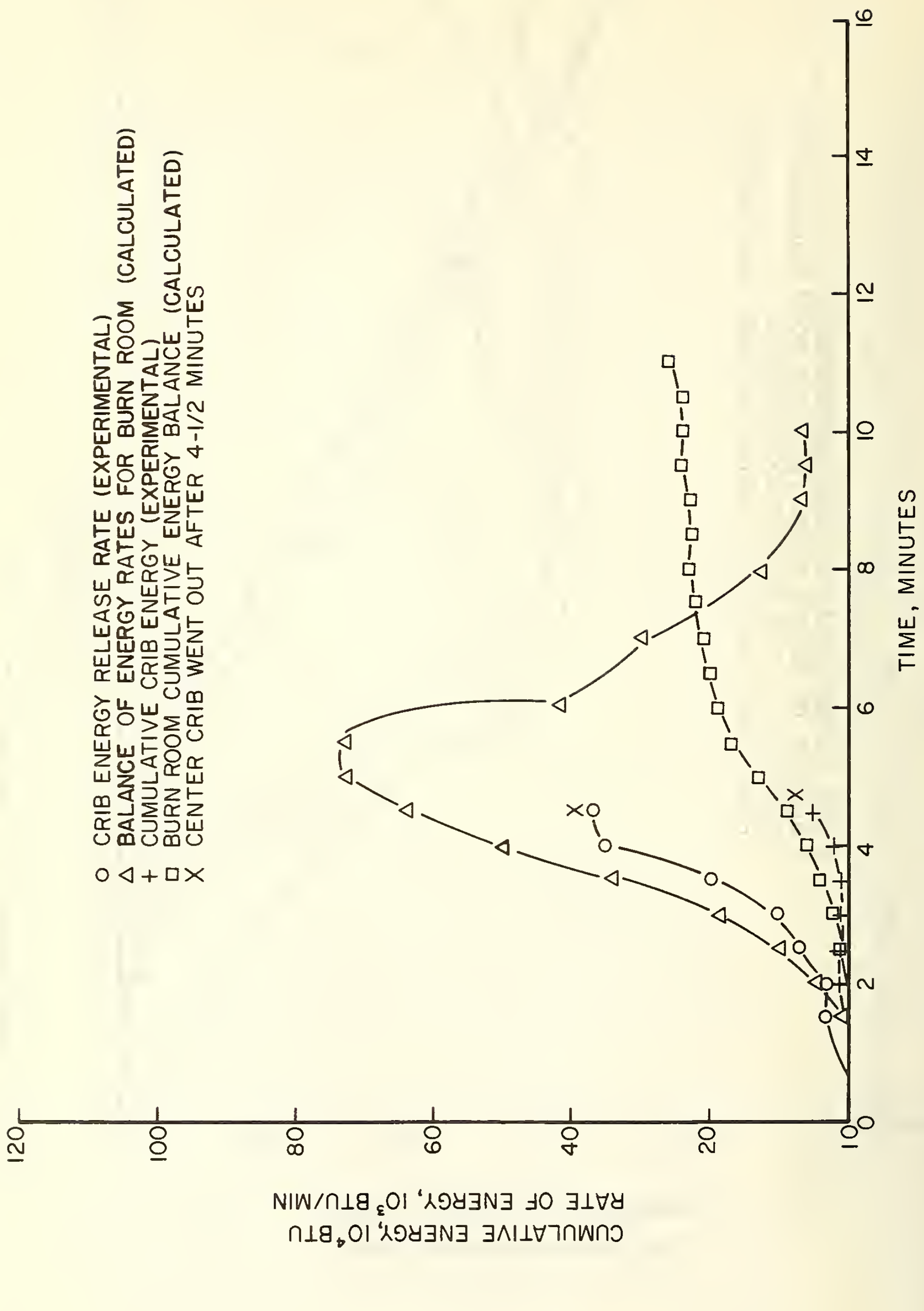

FIG. 13 BURN ROOM HEAT BALANCE, TEST 342

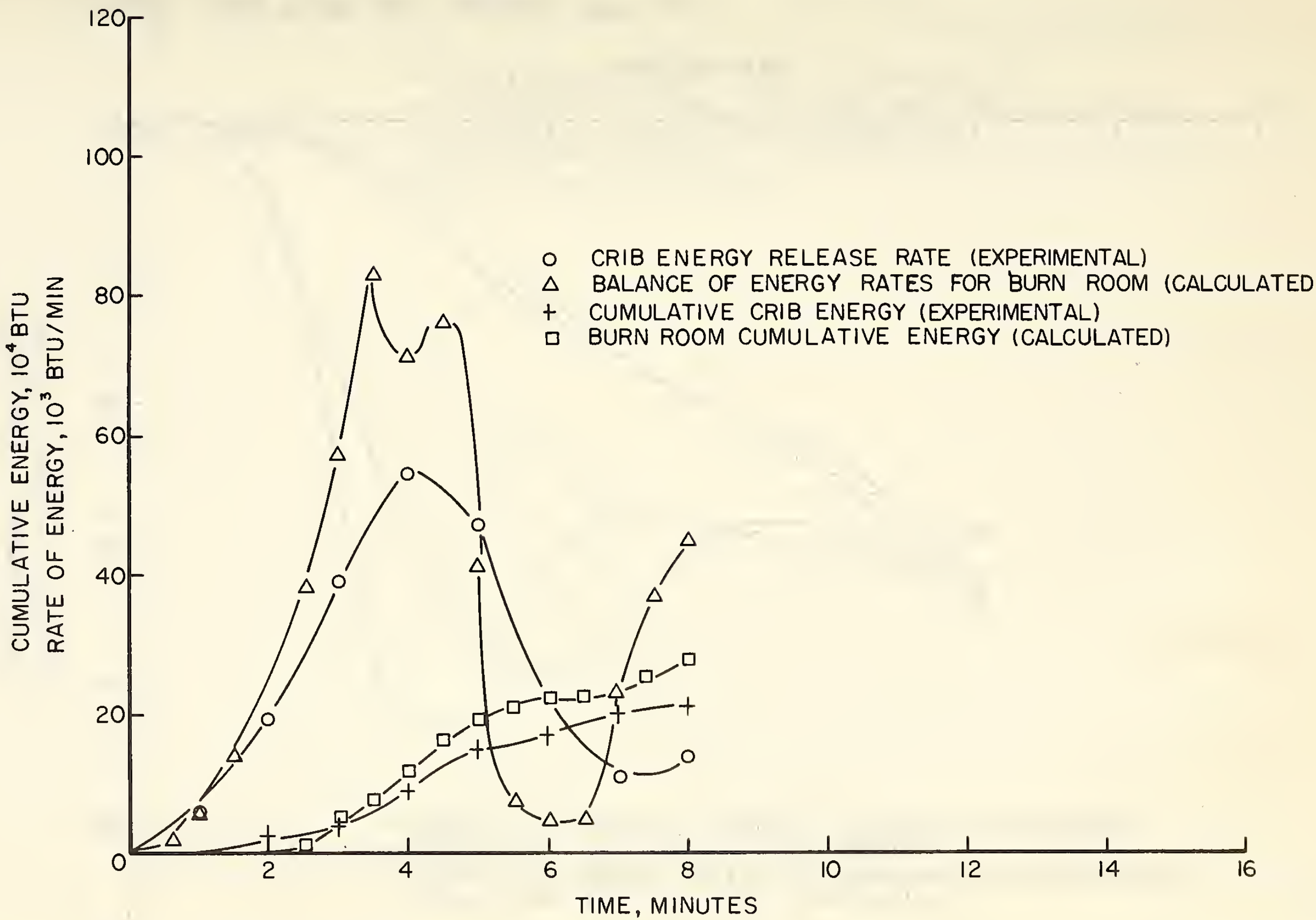

FIG. 14 BURN ROOM HEAT BALANCE, TEST 343

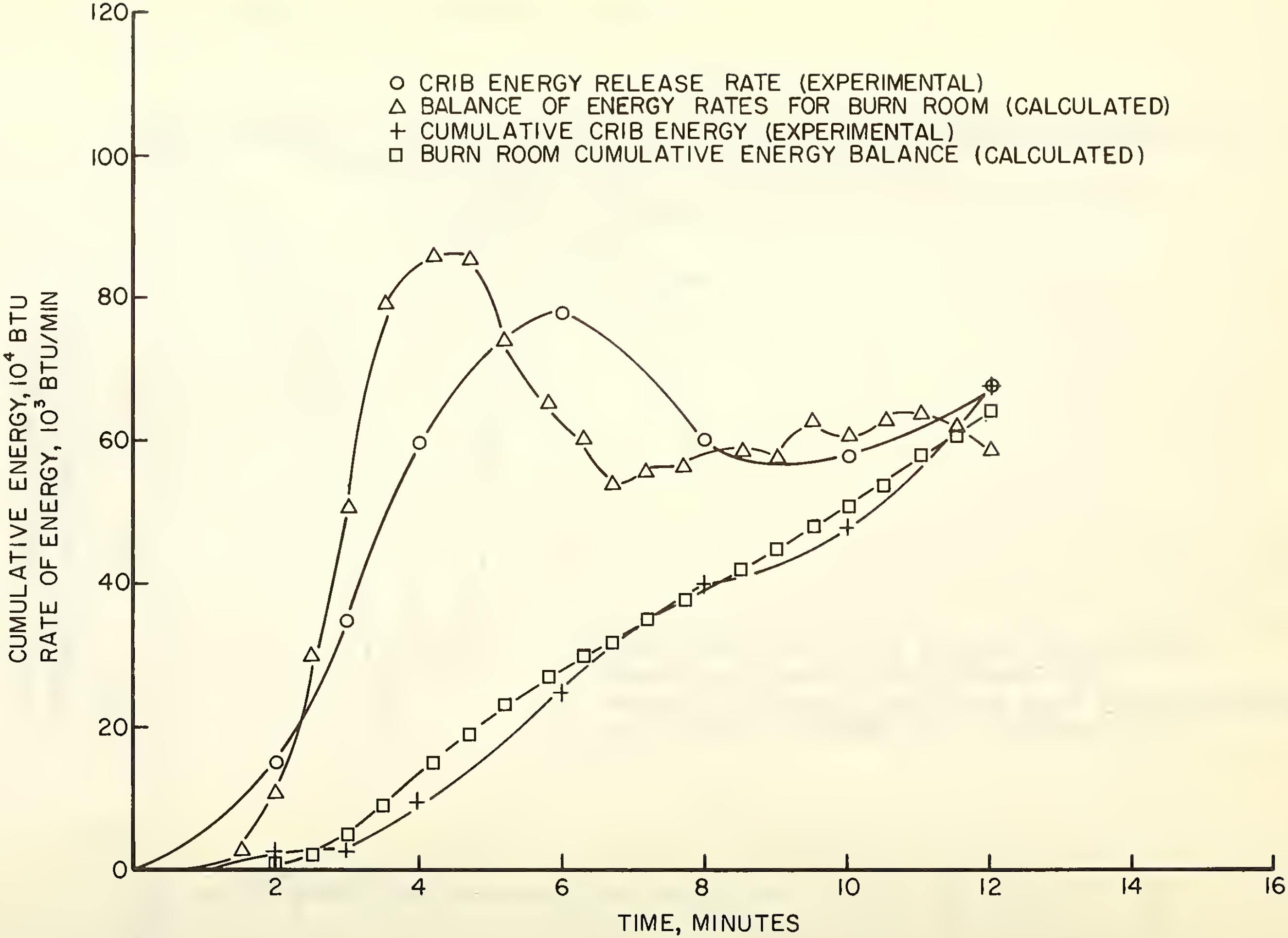

FIG. 15 BURN ROOM HEAT BALANCE, TEST 344

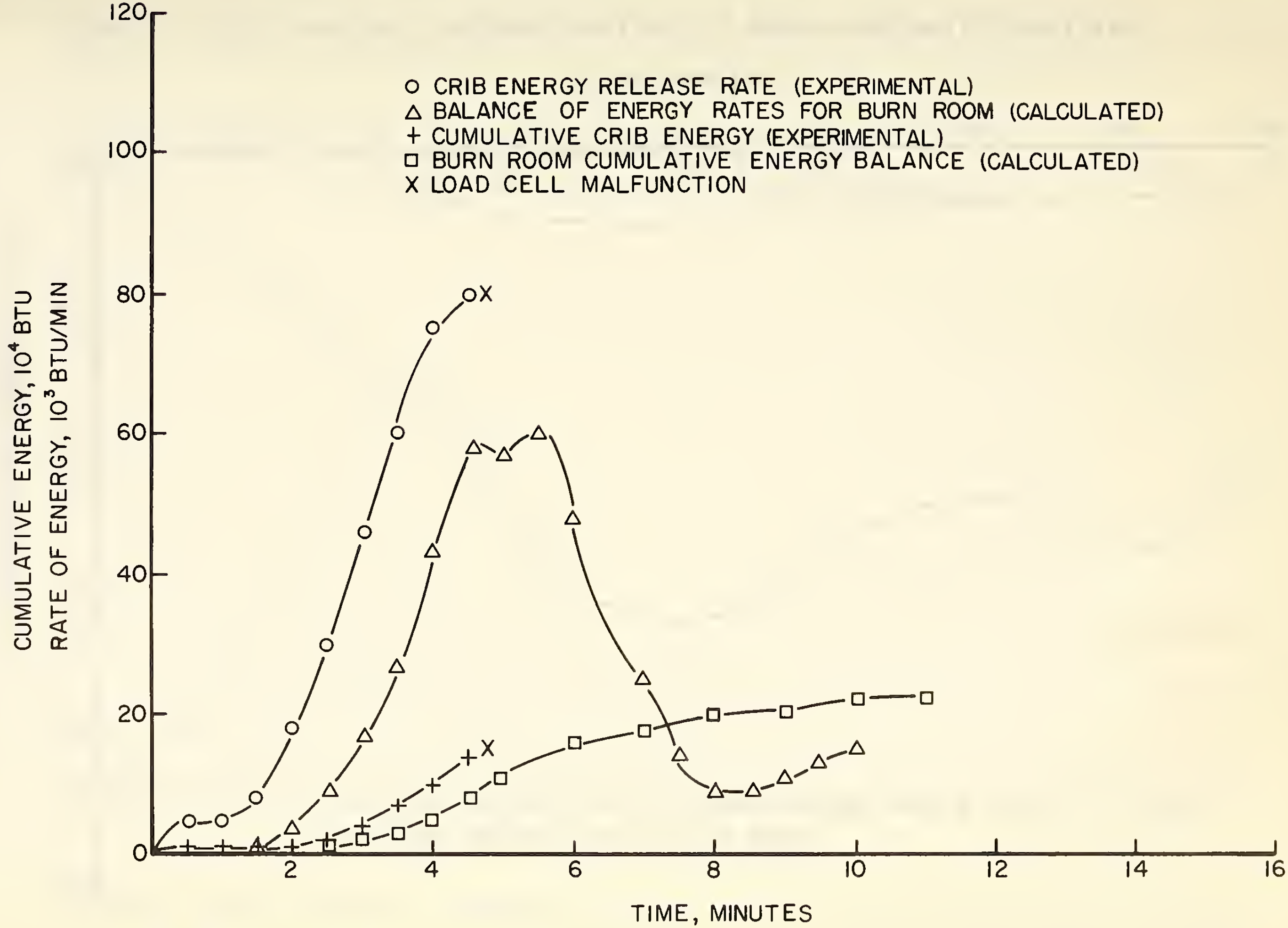

FIG. 16 BURN ROOM HEAT BALANCE, TEST 345

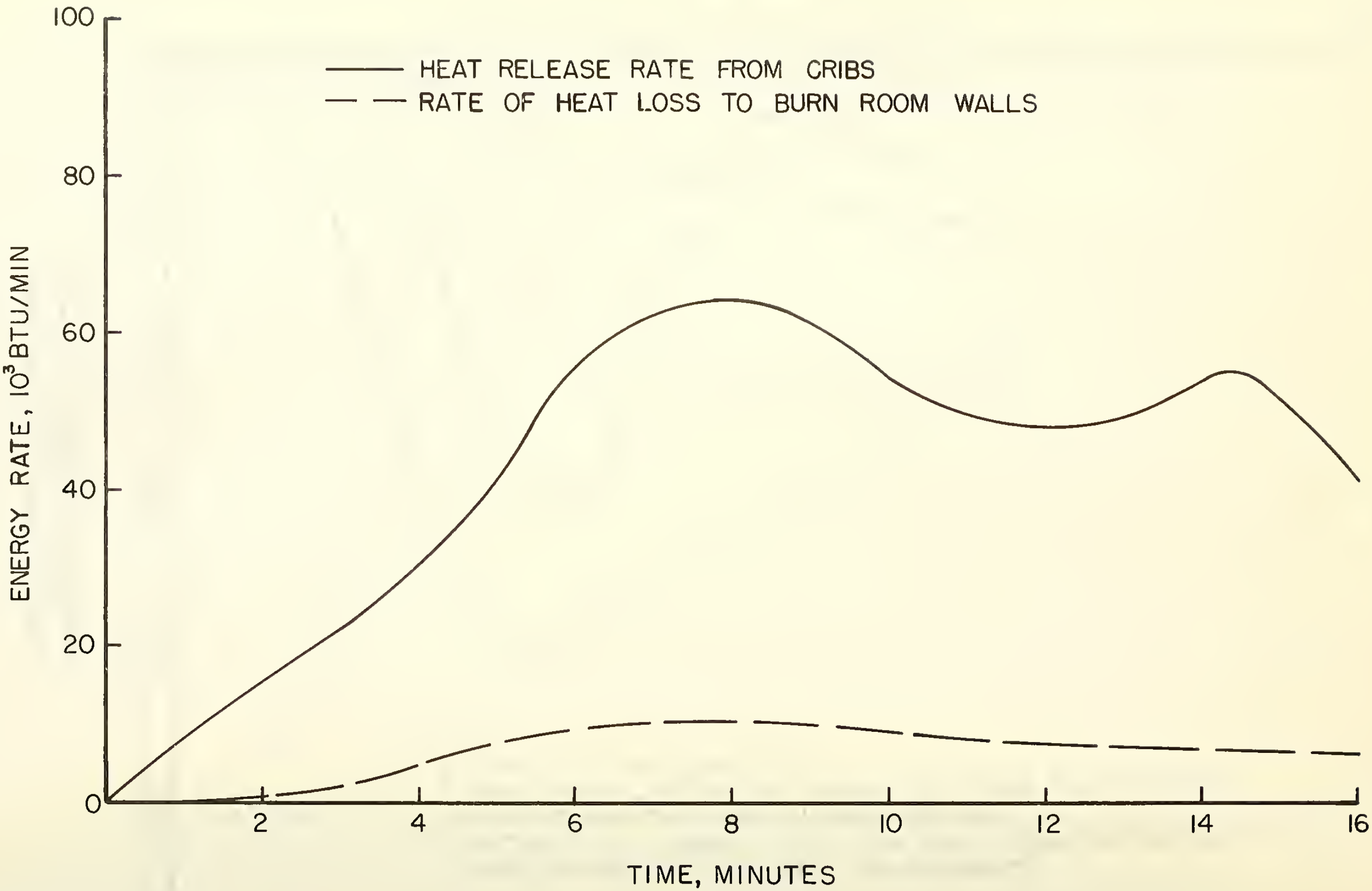

FIG. 17 TOTAL CRIB HEAT RELEASE AND LOSS TO BURN ROOM WALLS, TEST 339

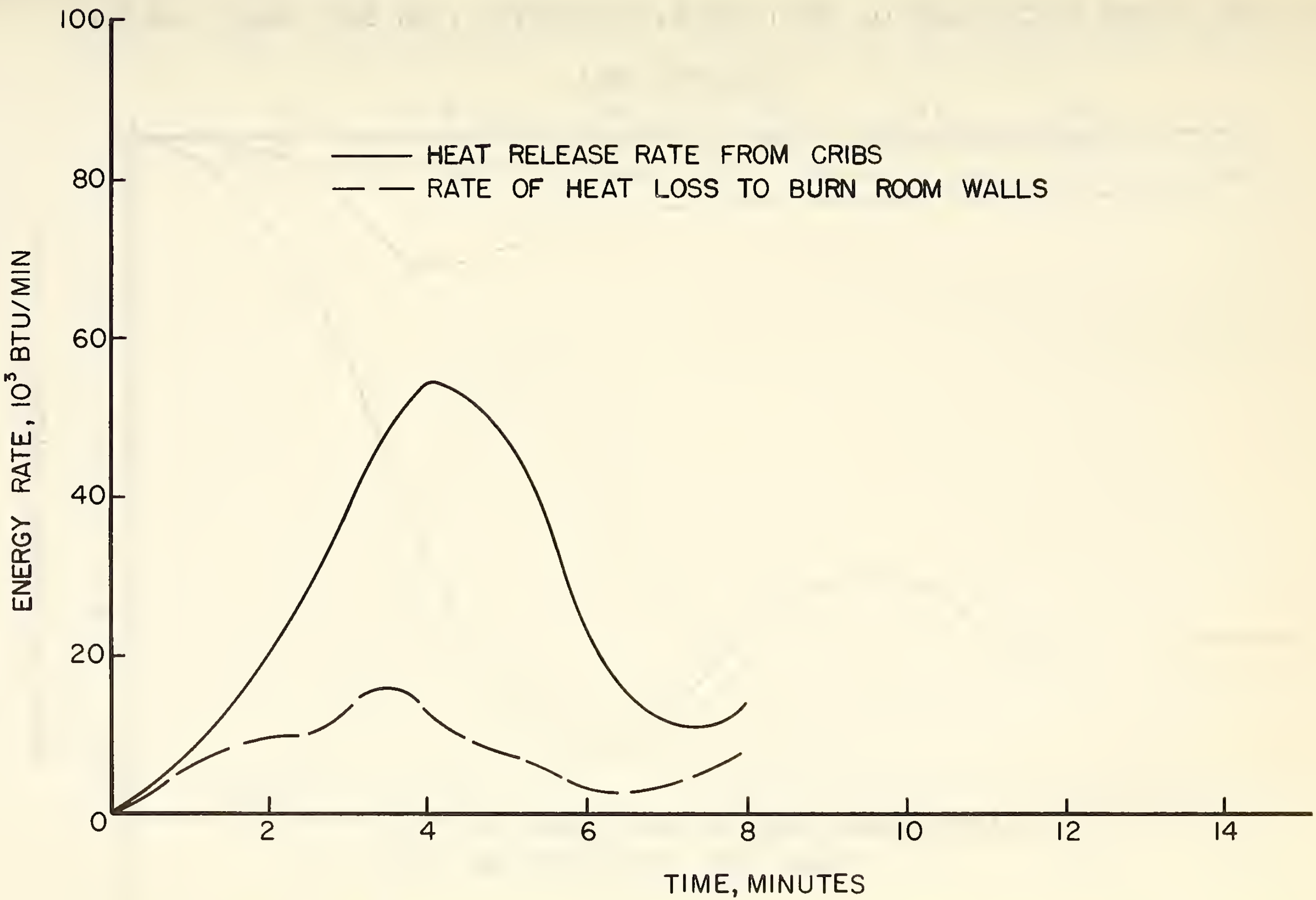

FIG. 18 TOTAL CRIB HEAT RELEASE RATE AND LOSS TO BURN ROOM WALLS, TEST 343

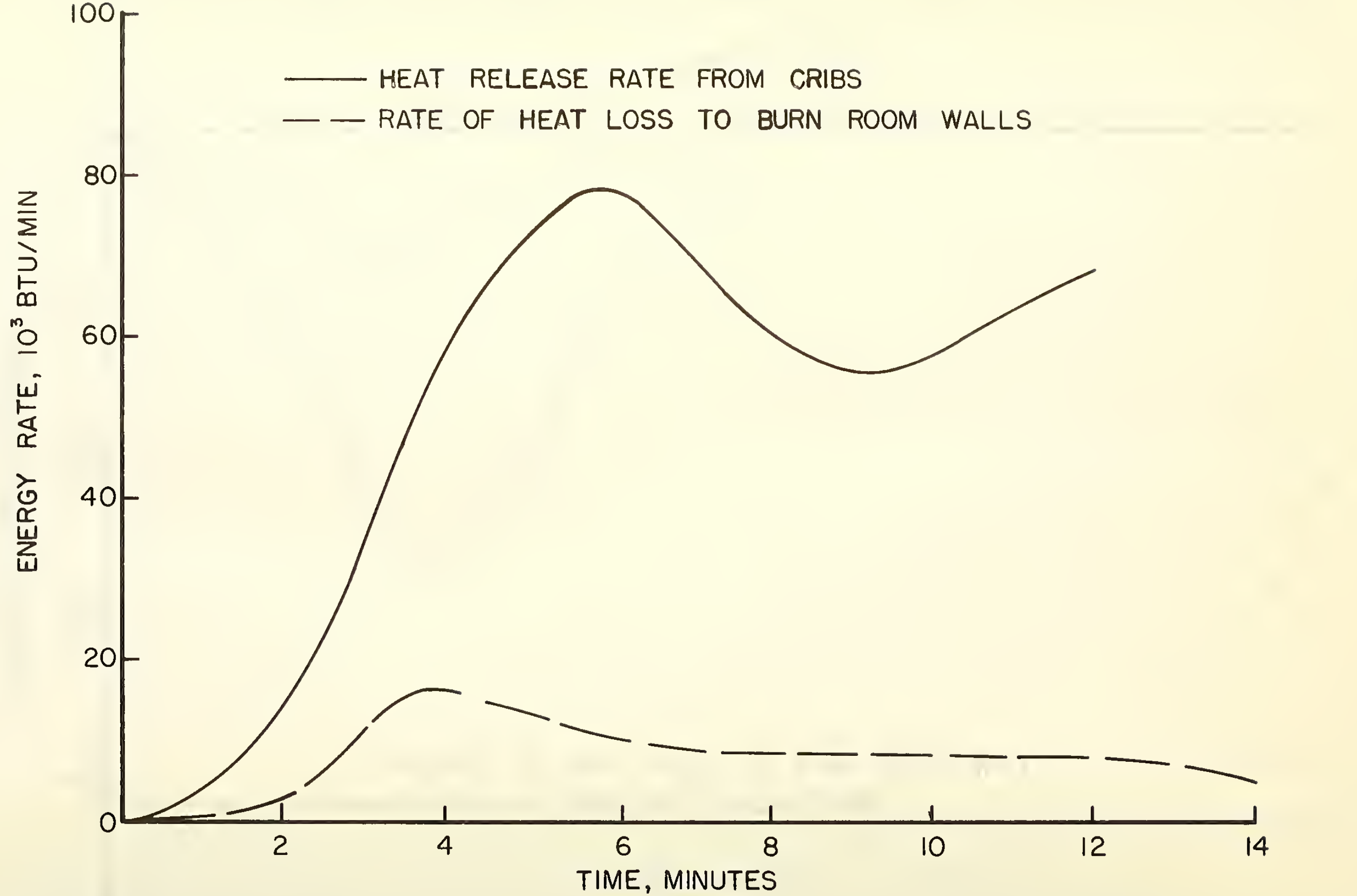

FIG. 19 TOTAL CRIB HEAT RELEASE RATE AND LOSS TO BURN ROOM WALLS, TEST 344

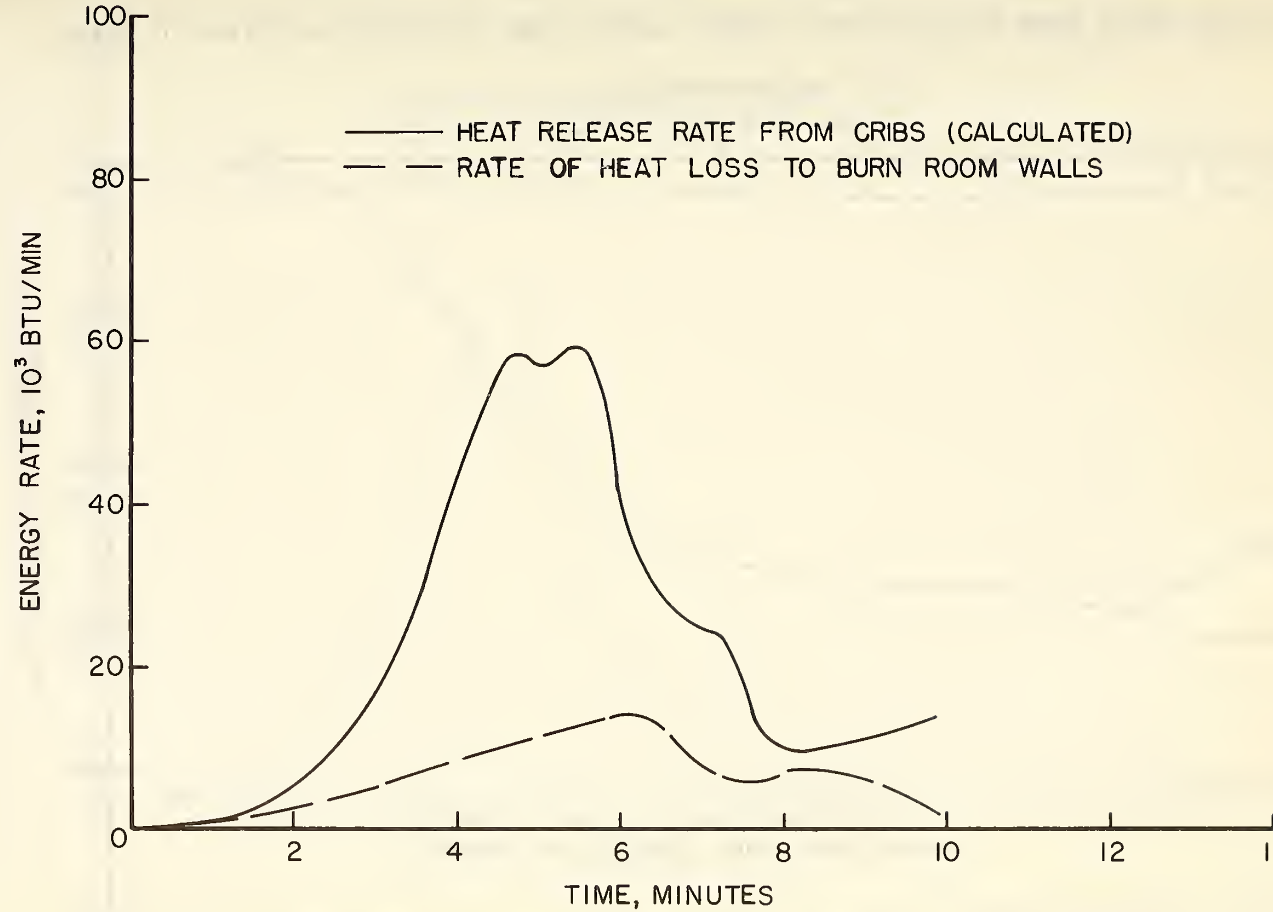

FIG. 20 TOTAL CRIB HEAT RELEASE RATE AND LOSS TO BURN ROOM WALLS, TEST 345

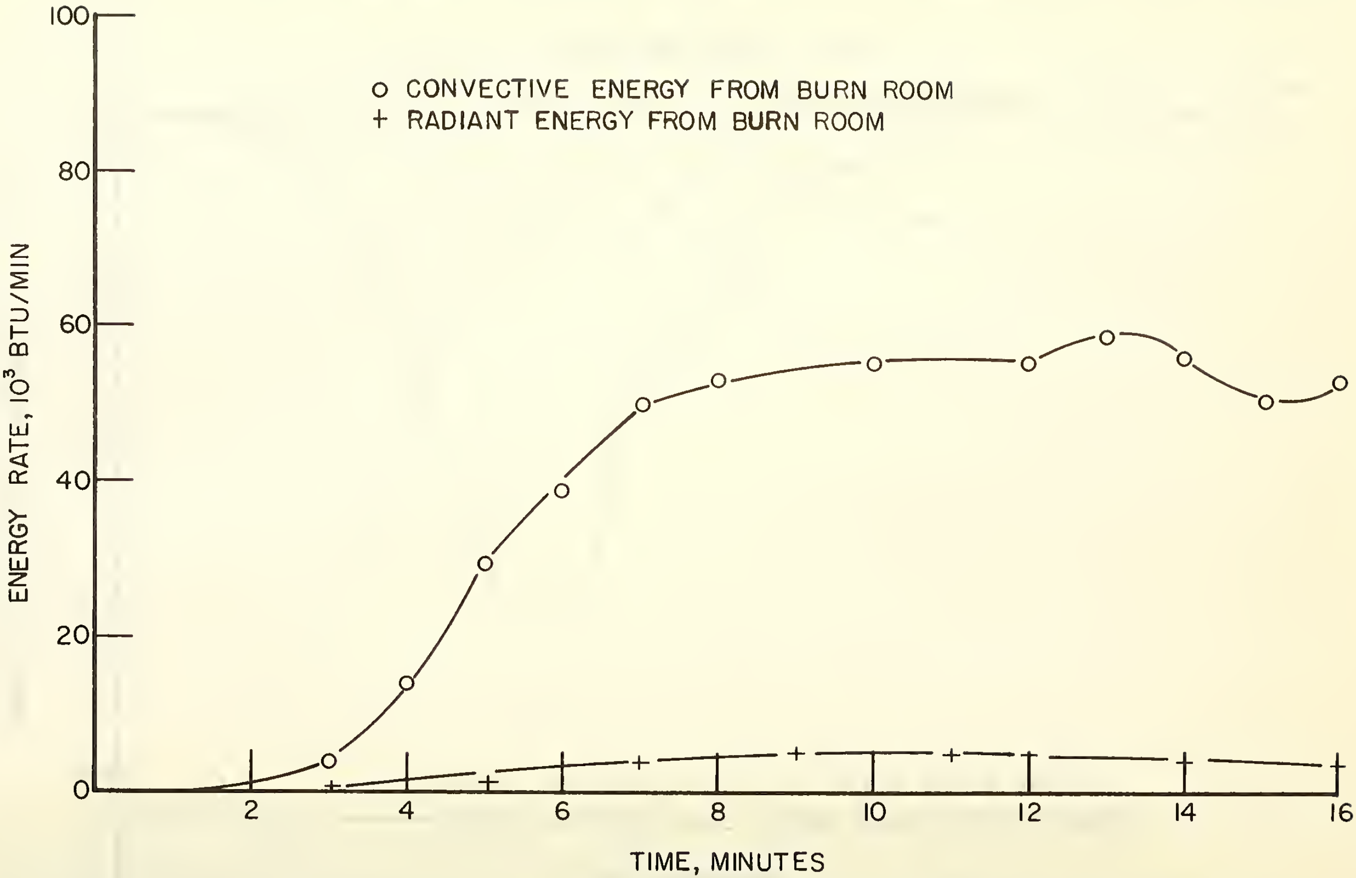

FIG. 21 RATE OF CONVECTIVE AND RADIANT ENERGY RELEASE FROM BURN ROOM, TEST 339

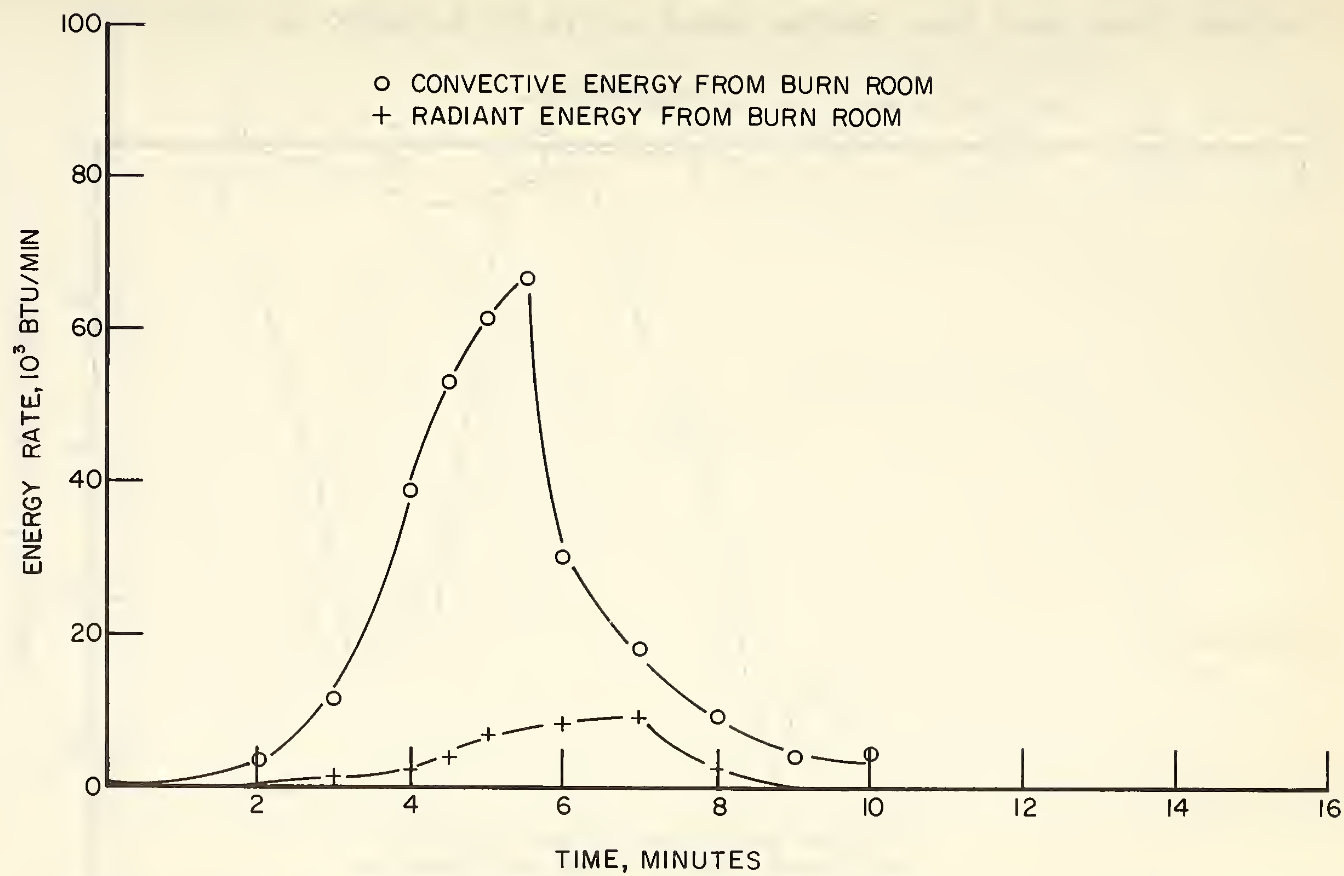

FIG. 22 RATE OF CONVECTIVE AND RADIANT ENERGY RELEASE FROM BURN ROOM, TEST 342

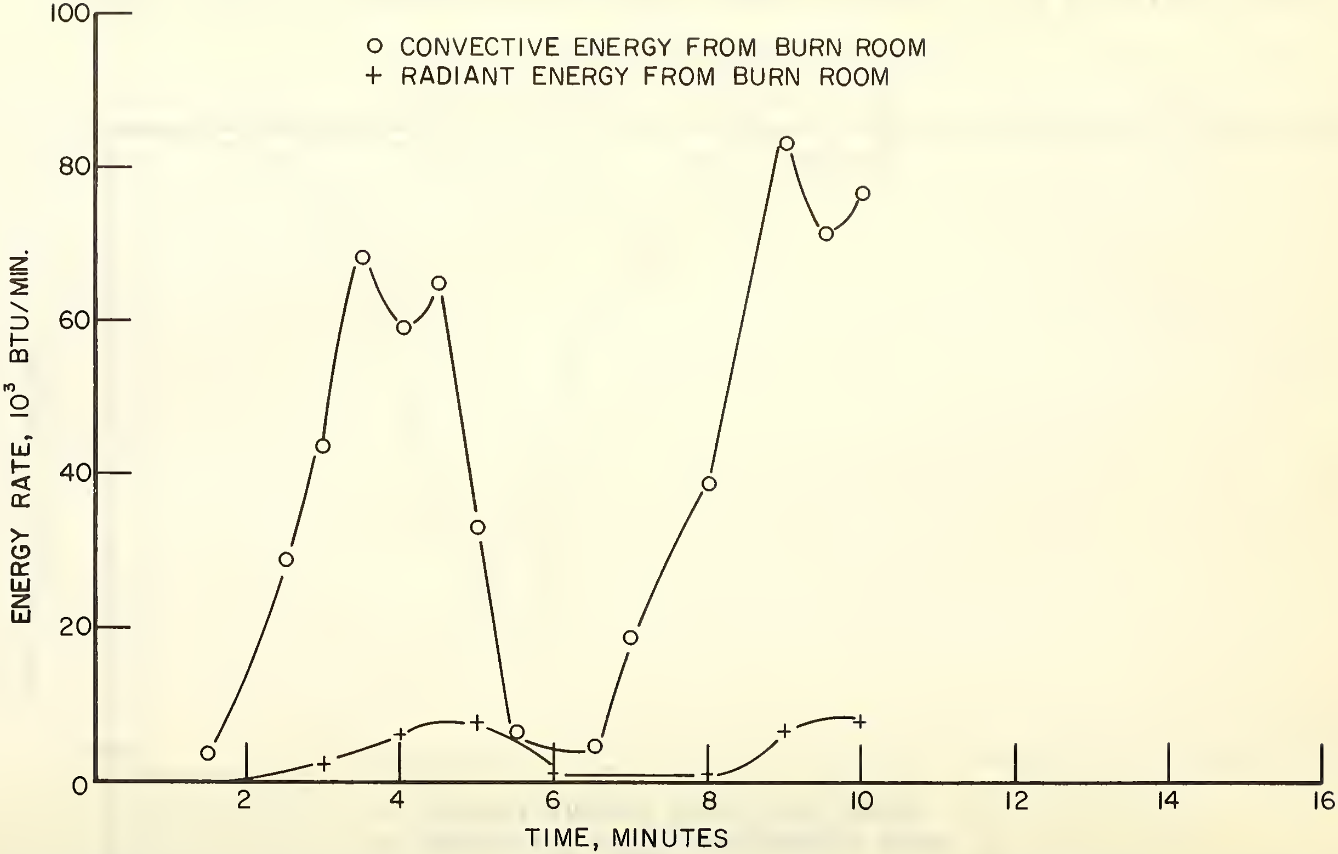

FIG. 23 RATE OF CONVECTIVE AND RADIANT ENERGY RELEASE FROM BURN ROOM, TEST 343

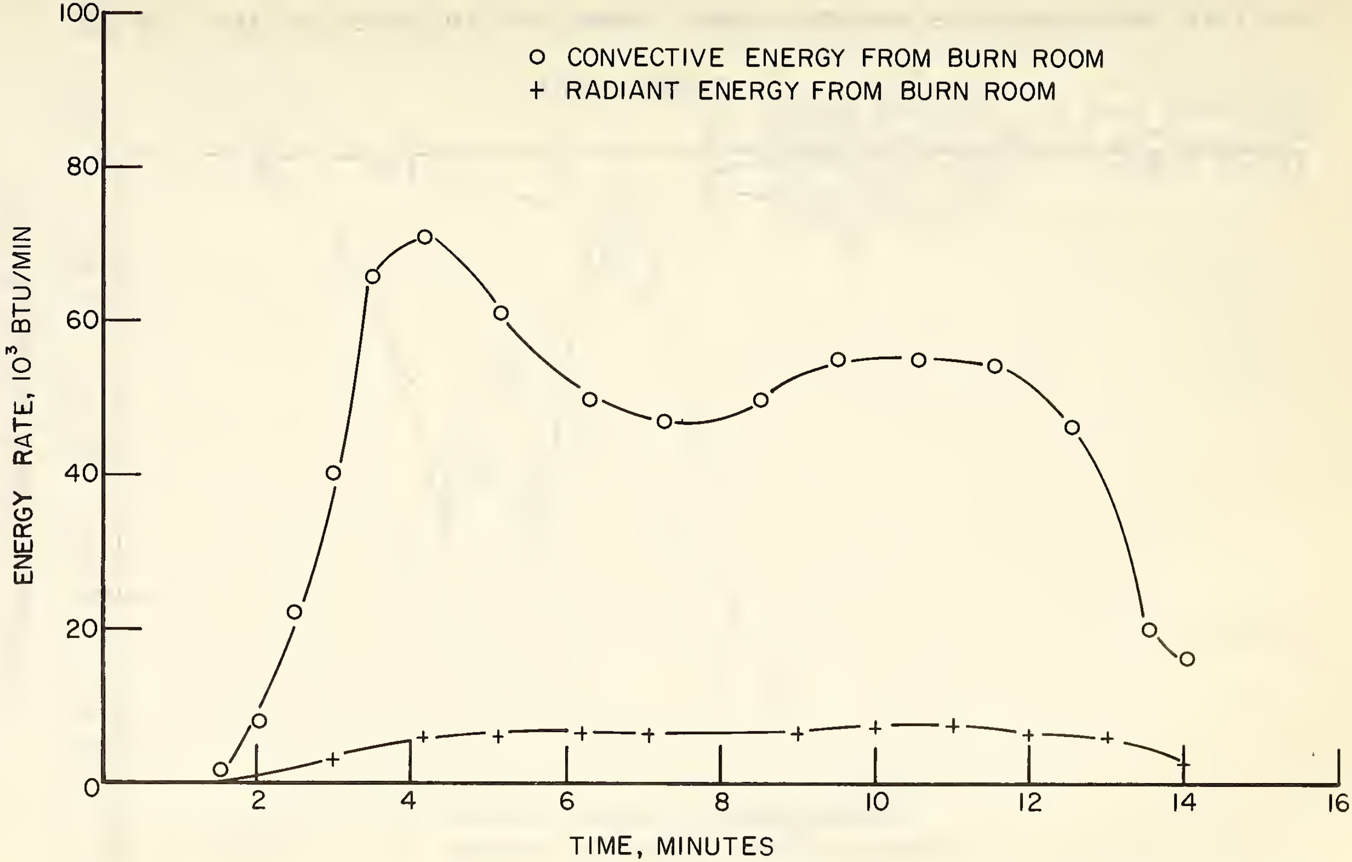

FIG. 24 RATE OF CONVECTIVE AND RADIANT ENERGY RELEASE FROM BURN ROOM, TEST 344

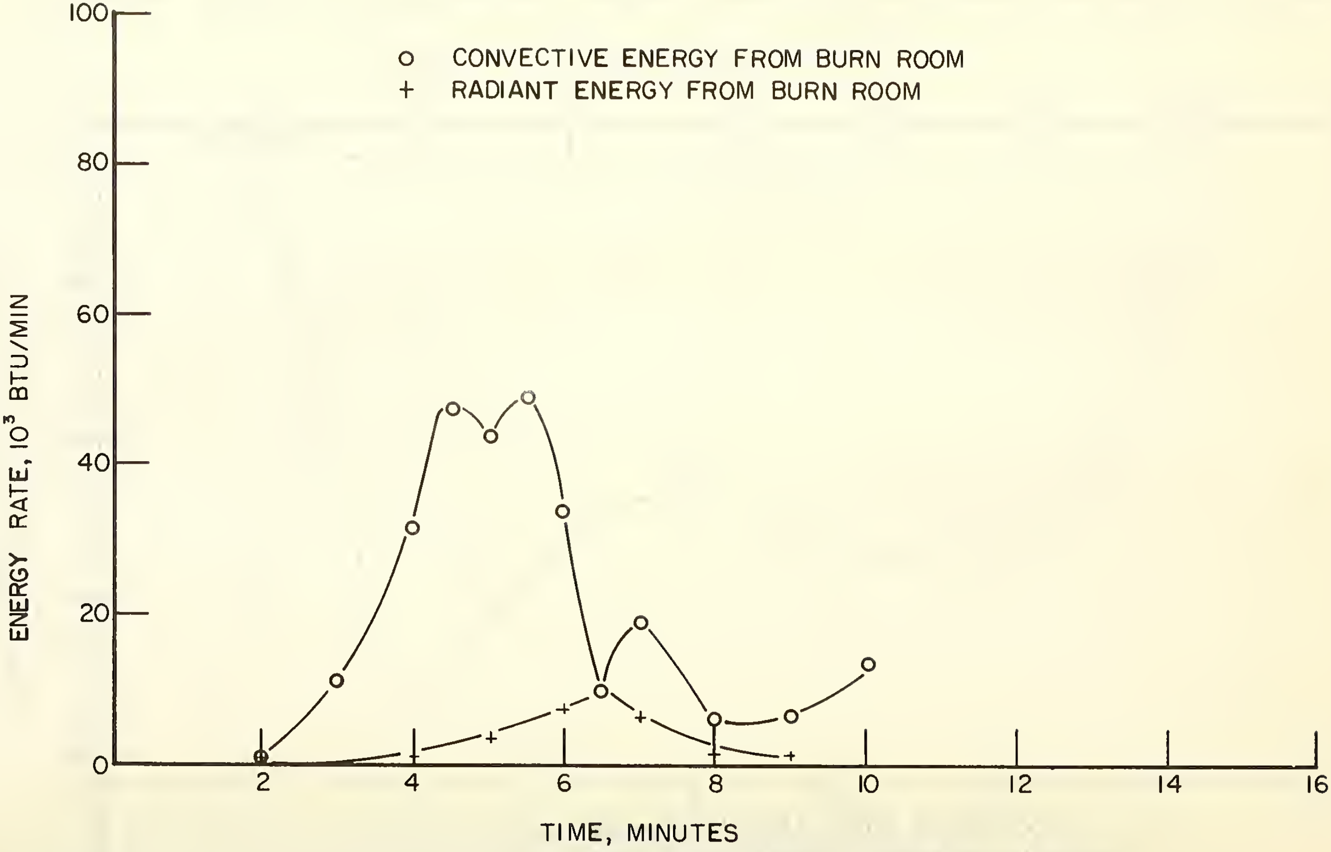

FIG. 25 RATE OF CONVECTIVE AND RADIANT ENERGY RELEASE FROM BURN ROOM, TEST 345

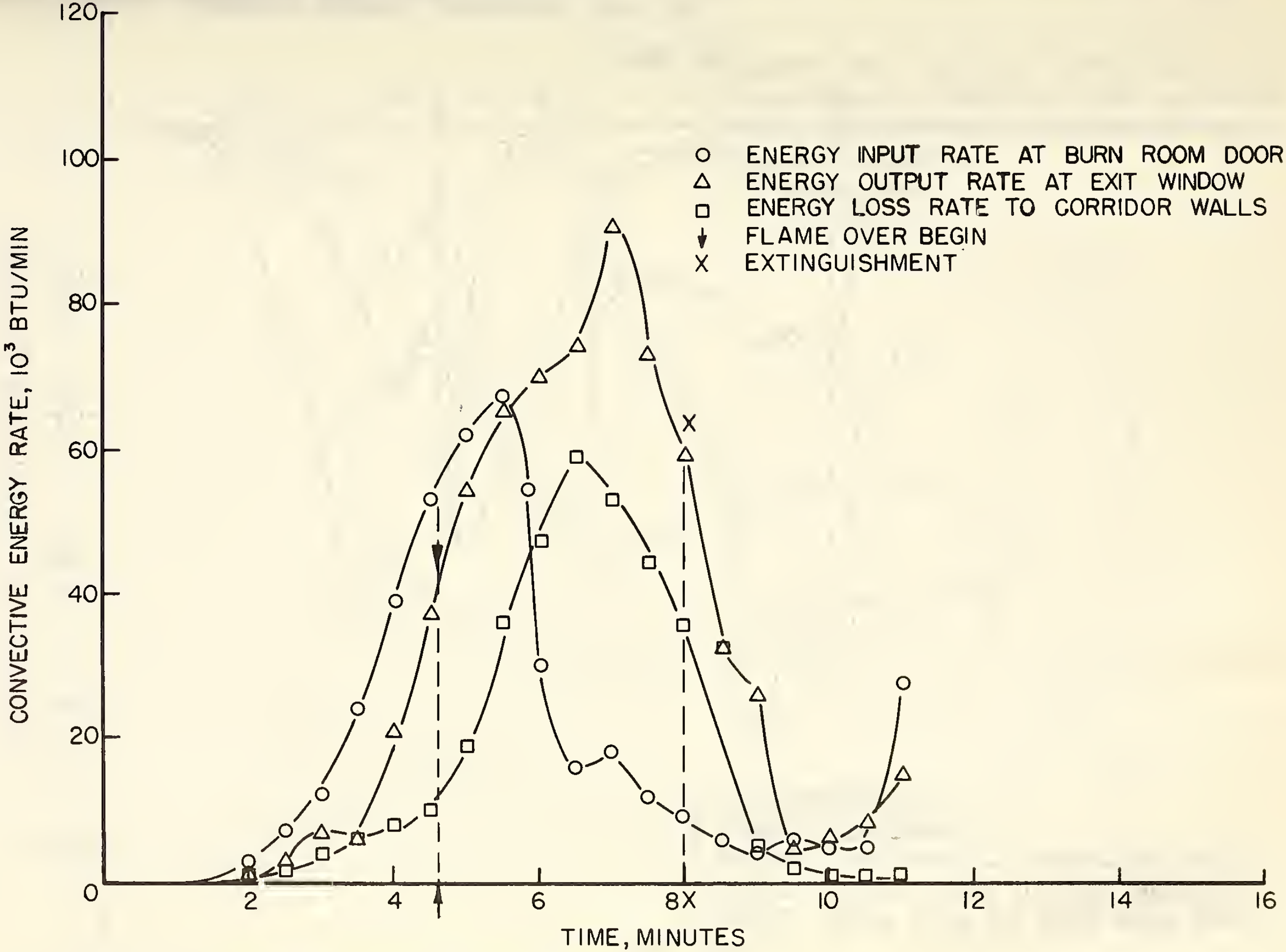

FIG. 26 CORRIDOR ENERGY COMPARISON, TEST 342

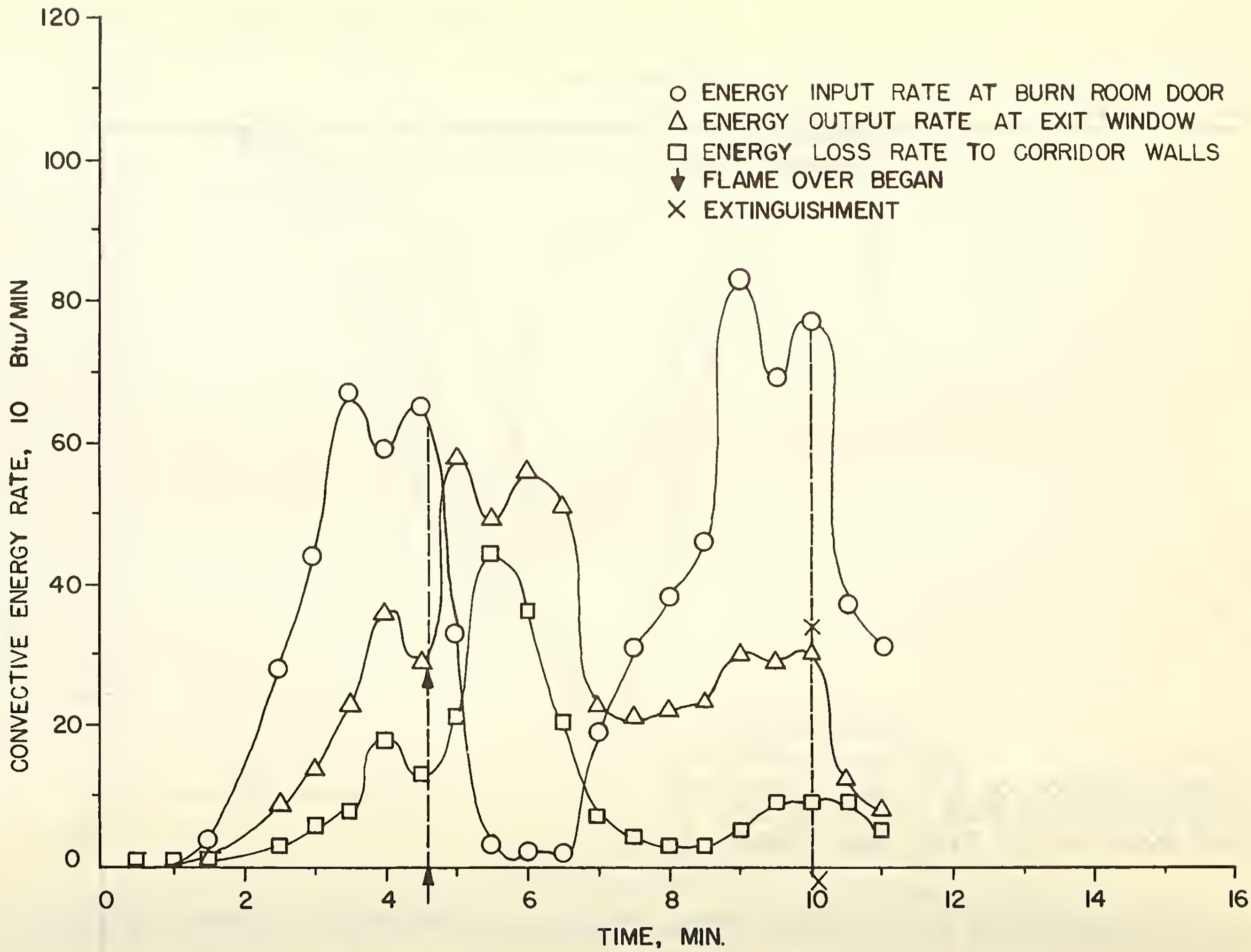

FIG. 27 CORRIDOR ENERGY COMPARISON, TEST 343

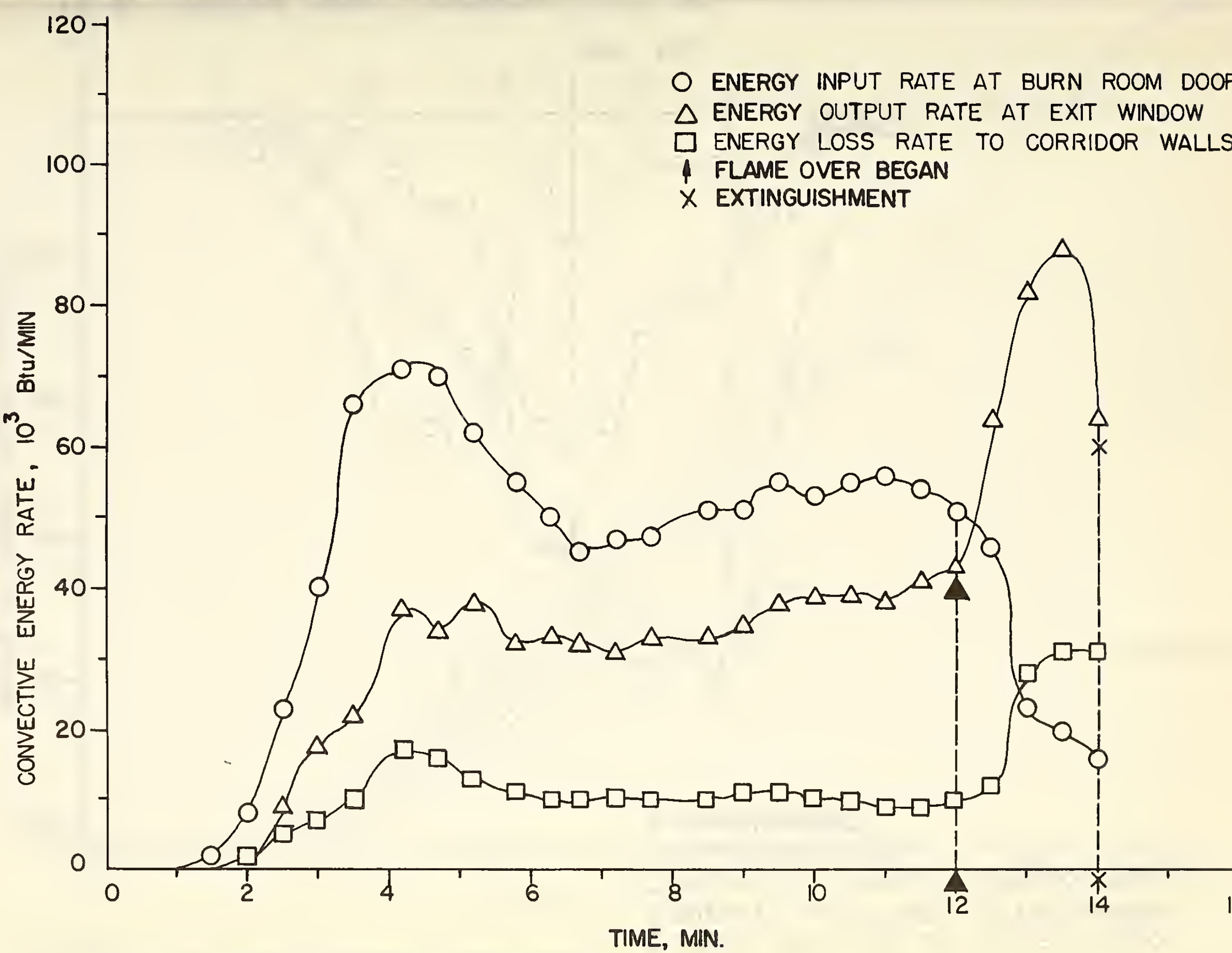

FIG. 28 CORRIDOR ENERGY COMPARISON, TEST 344

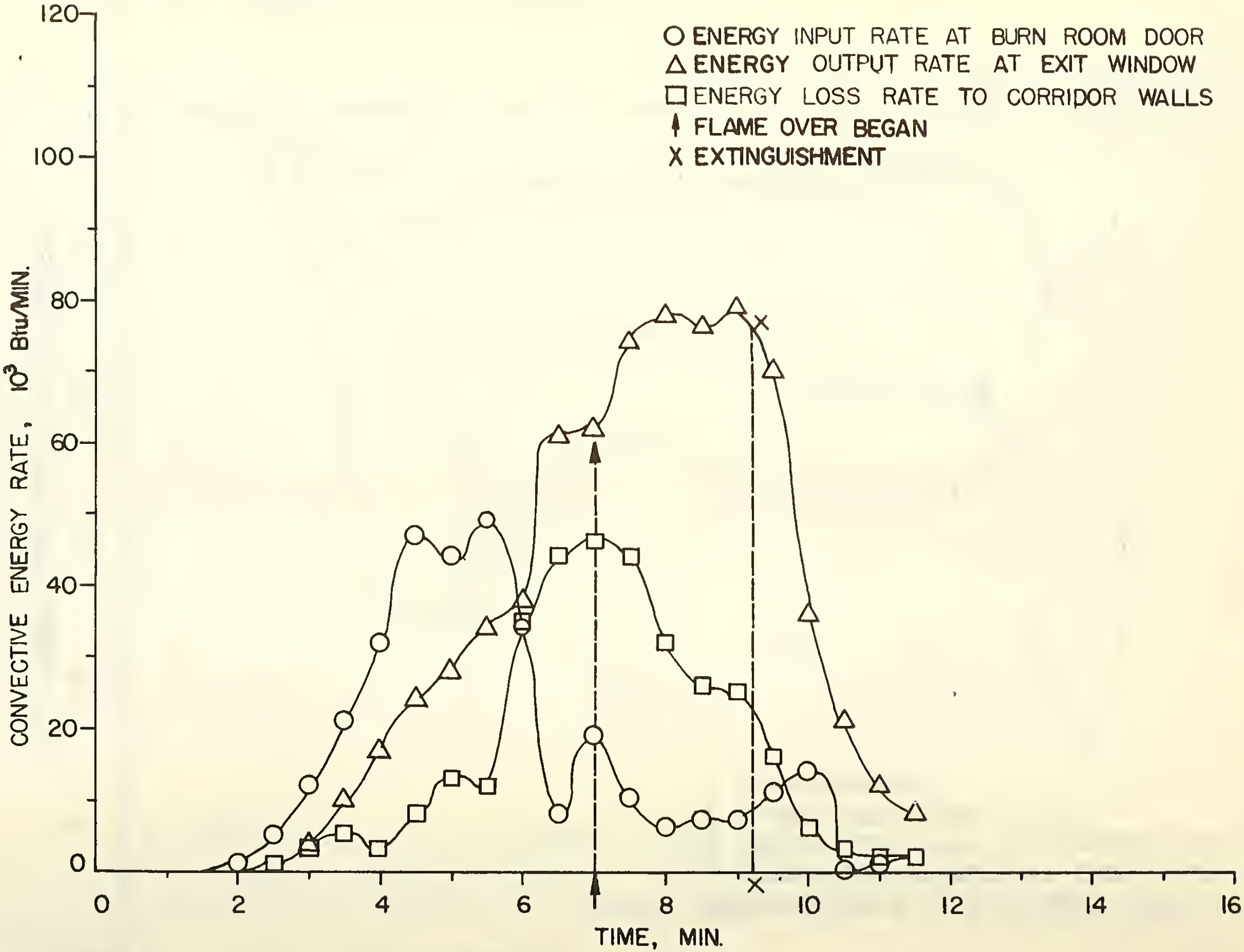

FIG. 29 CORRIDOR ENERGY COMPARISON, TEST 345

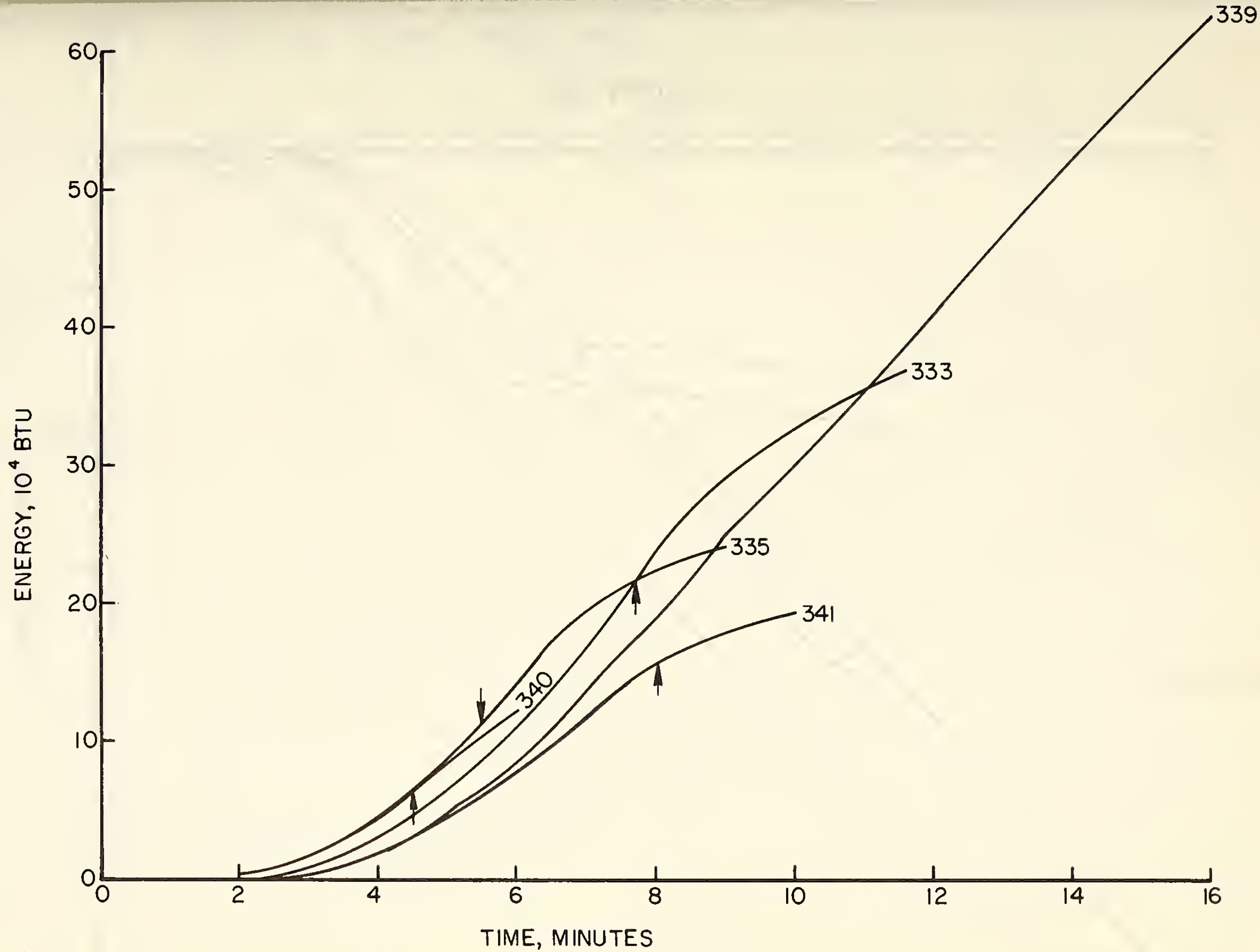

FIG. 30 CUMULATIVE CORRIDOR ENERGY INPUT

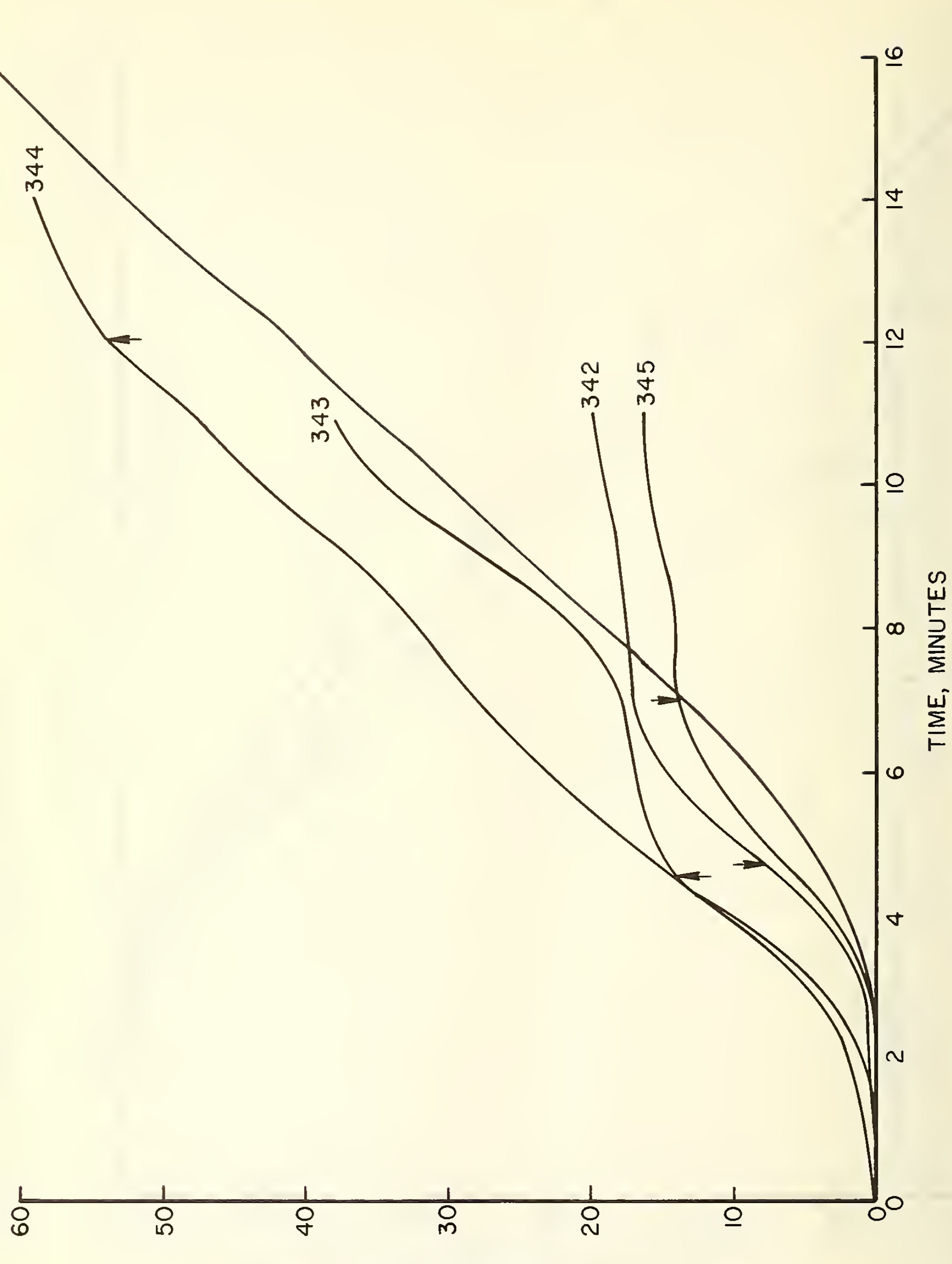

FIG. 31 CUMULATIVE CORRIDOR ENERGY INPUT

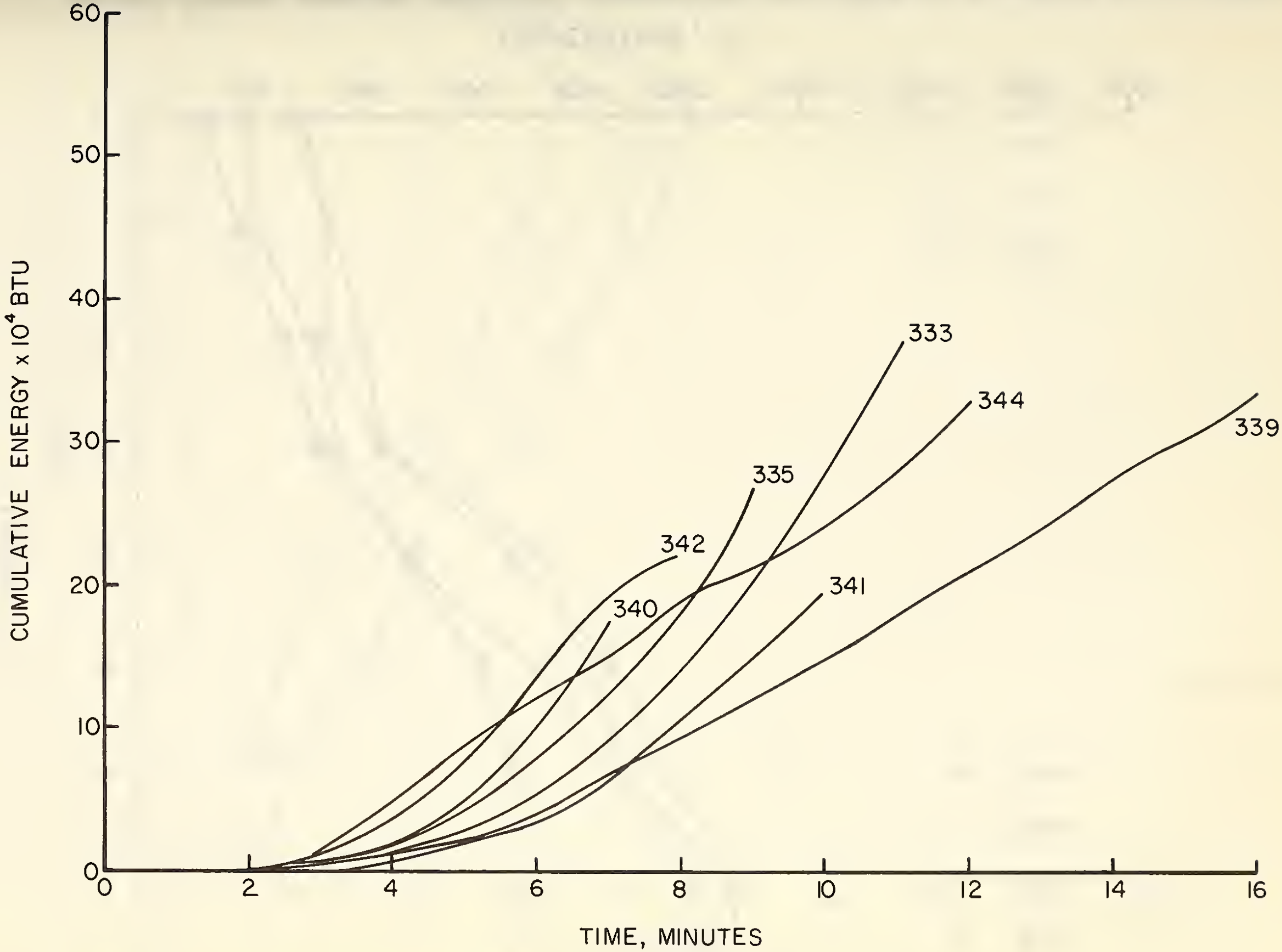

FIG. 32 CUMULATIVE CORRIDOR ENERGY OUTPUT

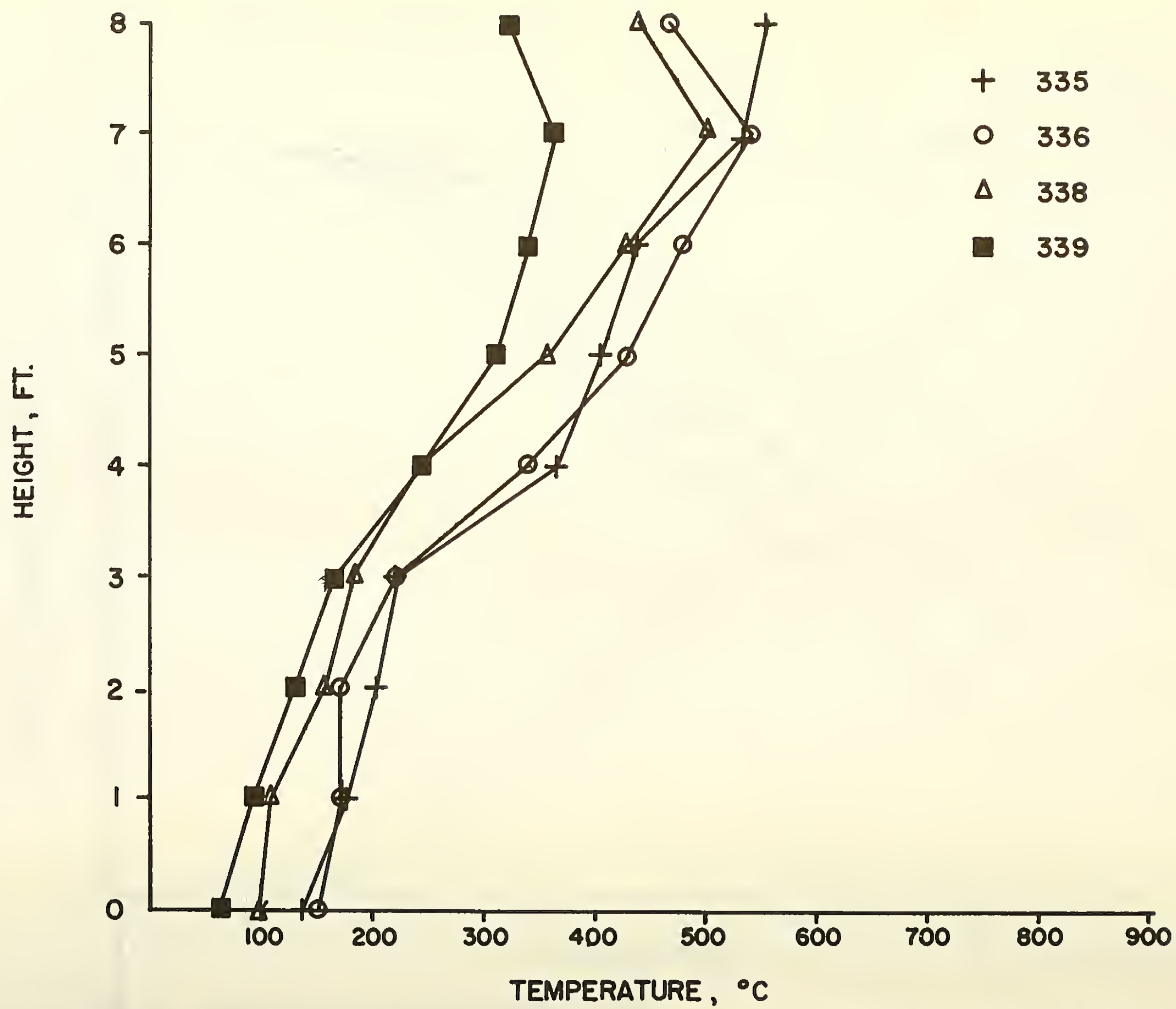

FIG. 33 TYPICAL CORRIDOR PREHEATING TEMPERATURE JUST PRIOR TO FLAMEOVER (10 ft. LOCATION)

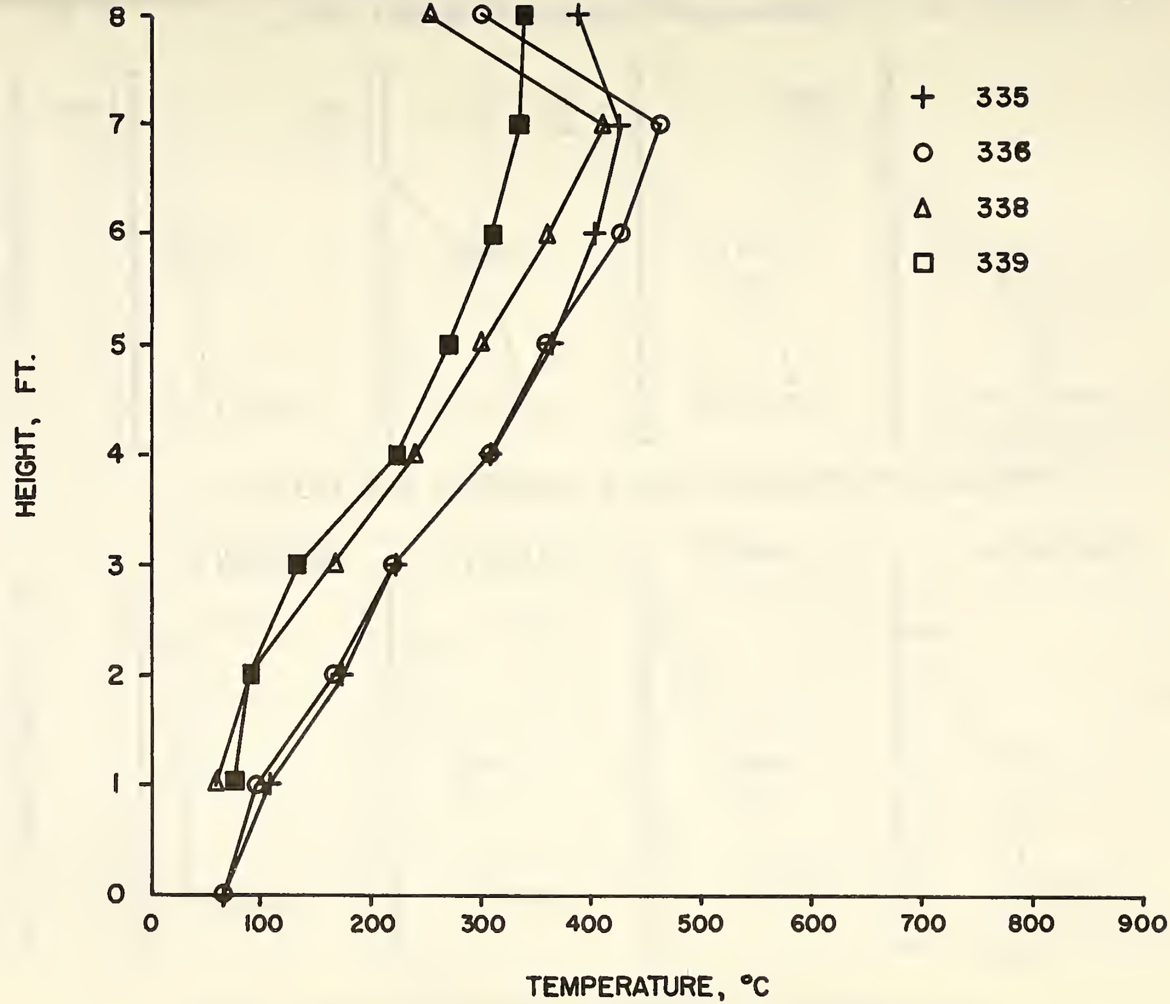

FIG. 34 TYPICAL CORRIDOR PREHEATING TEMPERATURE JUST PRIOR TO FLAMEOVER (20 ft. LOCATION)

TEST 339 TEMPERATURE PROFILE AT EXHAUST (°C)

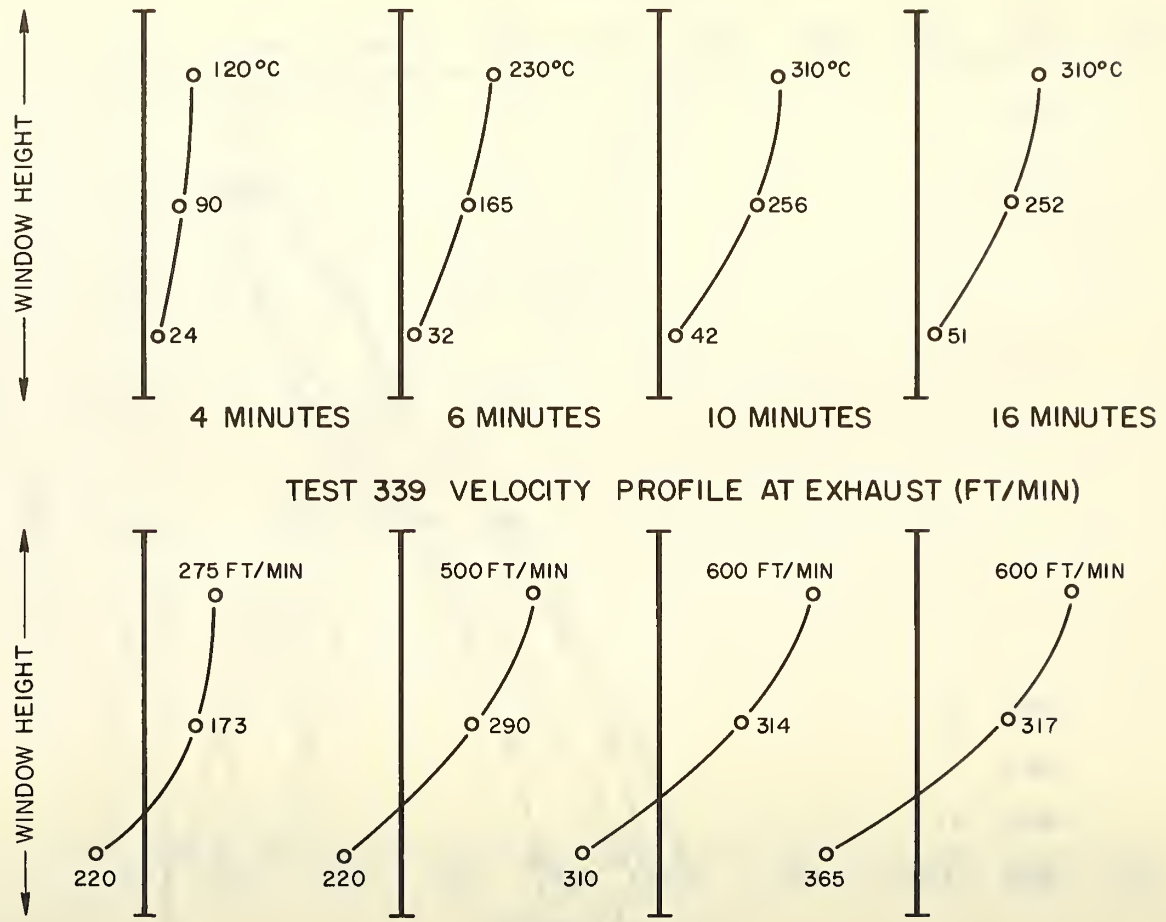

FIG. 35 GAS TEMPERATURE AND VELOCITY PROFILES AT EXIT WINDOW, TEST 339

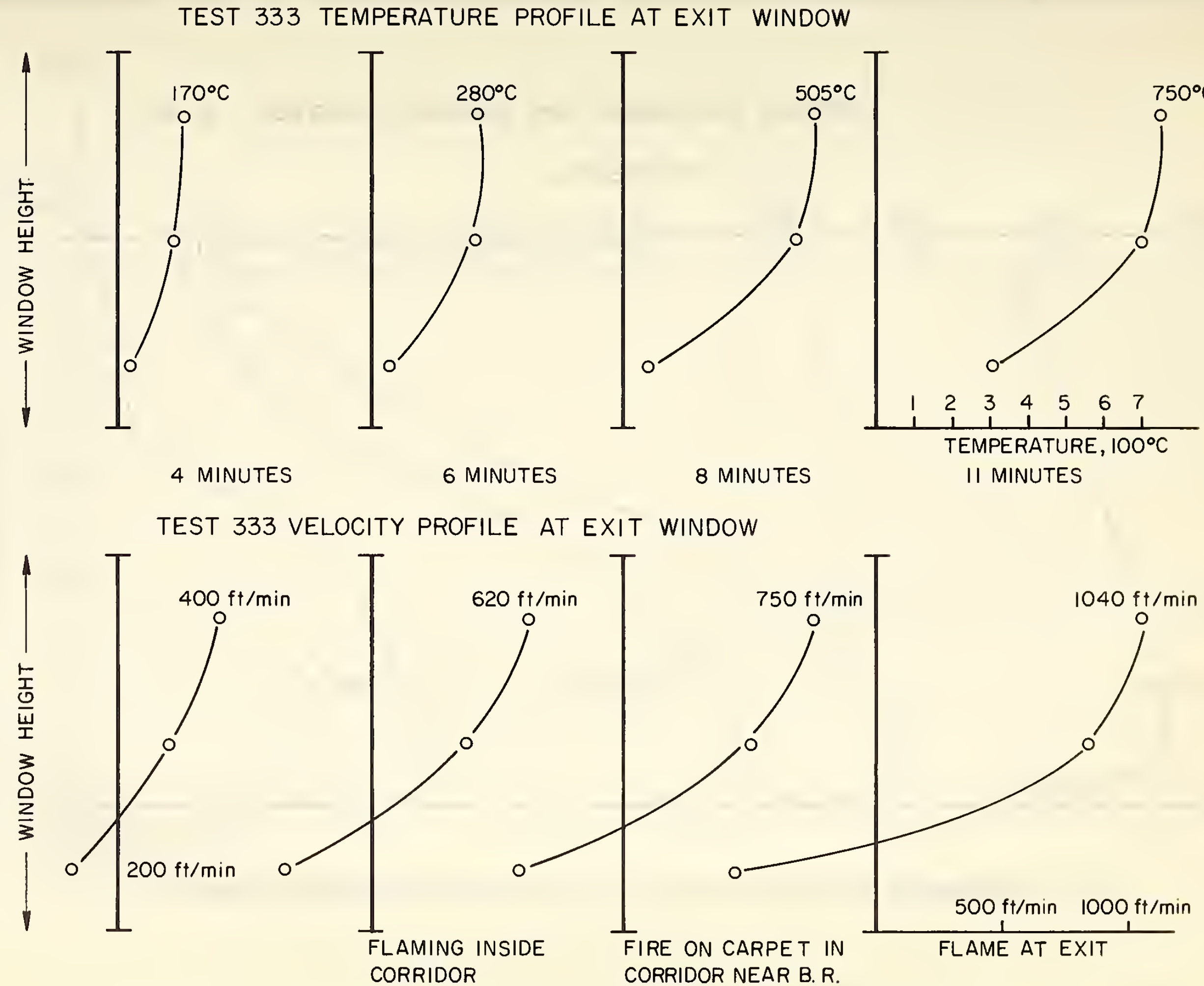

FIG. 36 GAS TEMPERATURE AND VELOCITY PROFILES AT EXIT WINDOW, TEST 333

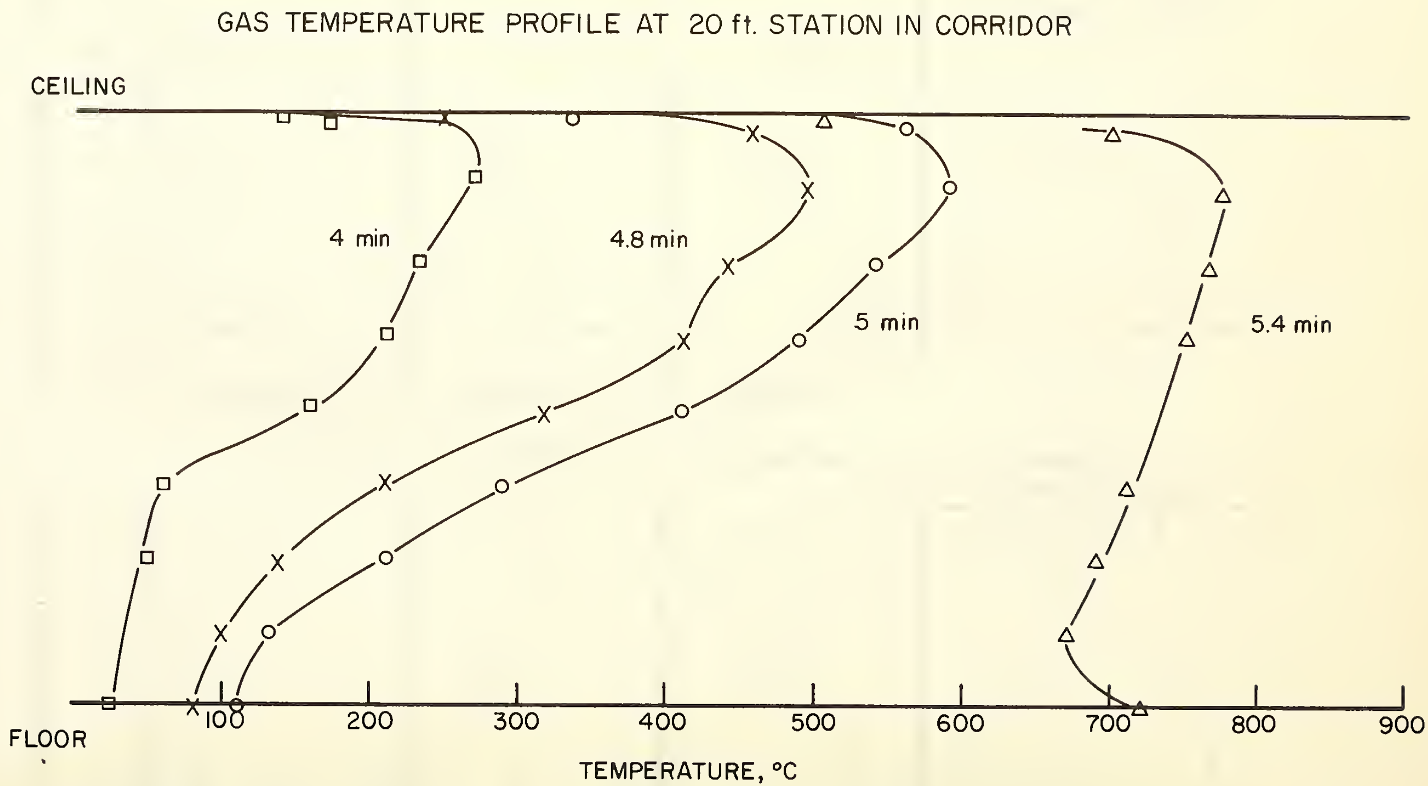

FIG. 37 SEQUENCIAL CORRIDOR GAS TEMPERATURE PROFILES

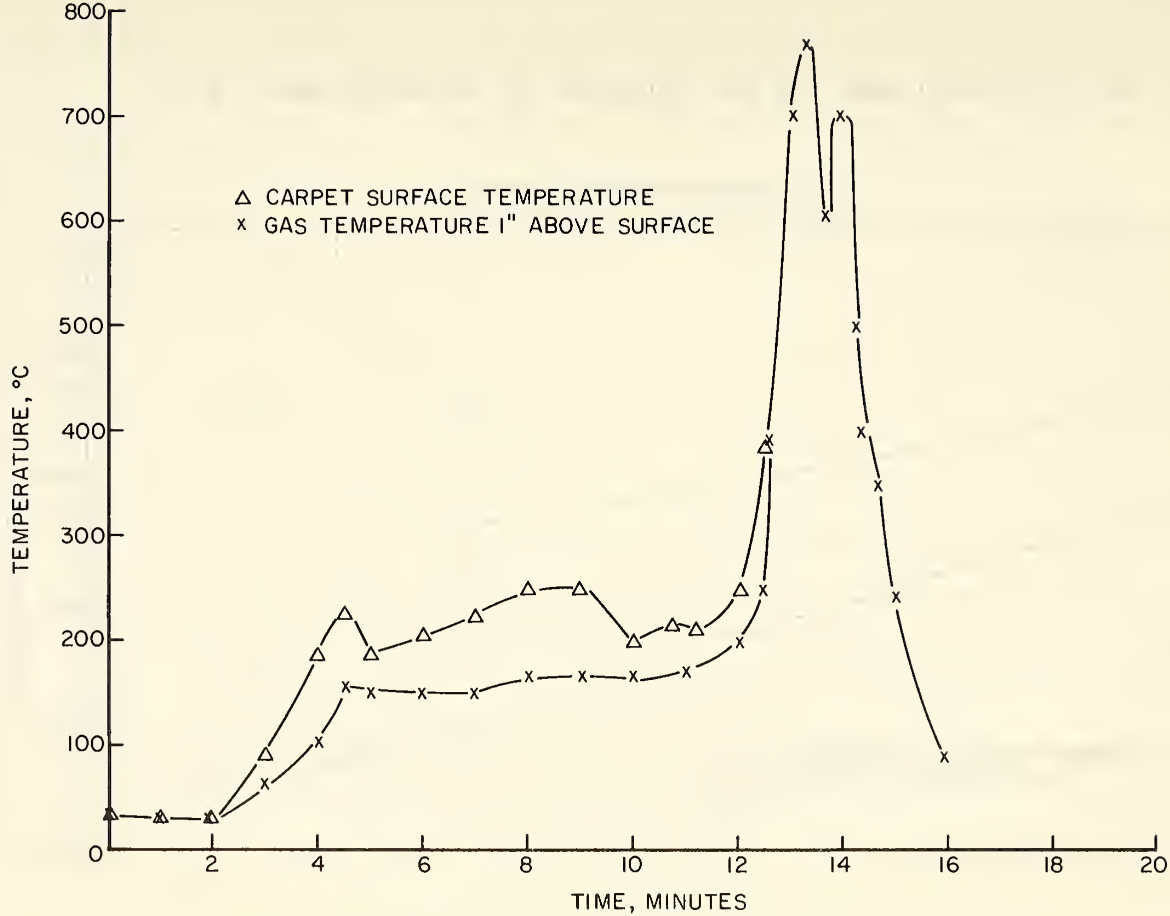

FIG. 38 CARPET SURFACE AND GAS TEMPERATURE ONE INCH ABOVE CARPET AT 7.5 FT. STATION, TEST 344

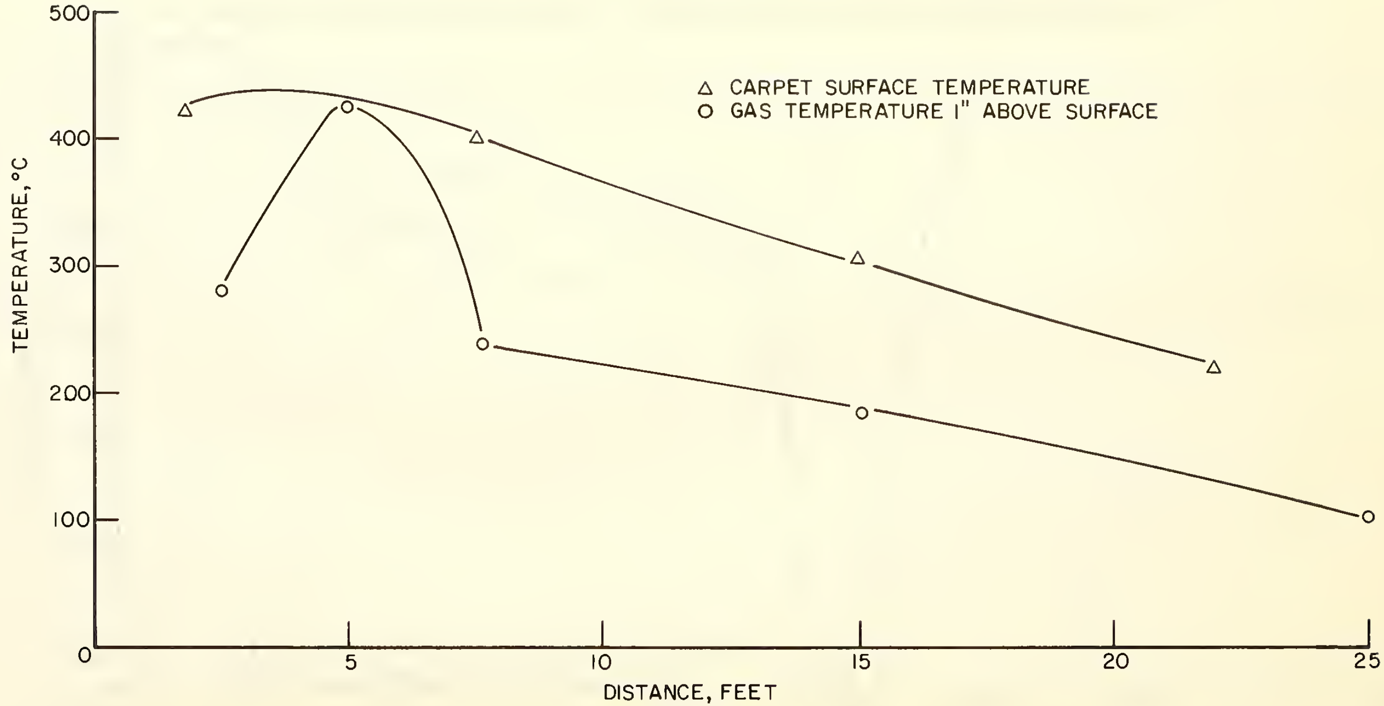

FIG. 39 CARPET SURFACE AND GAS TEMPERATURE ONE INCH ABOVE CARPET AT 12.5 MIN , TEST 344

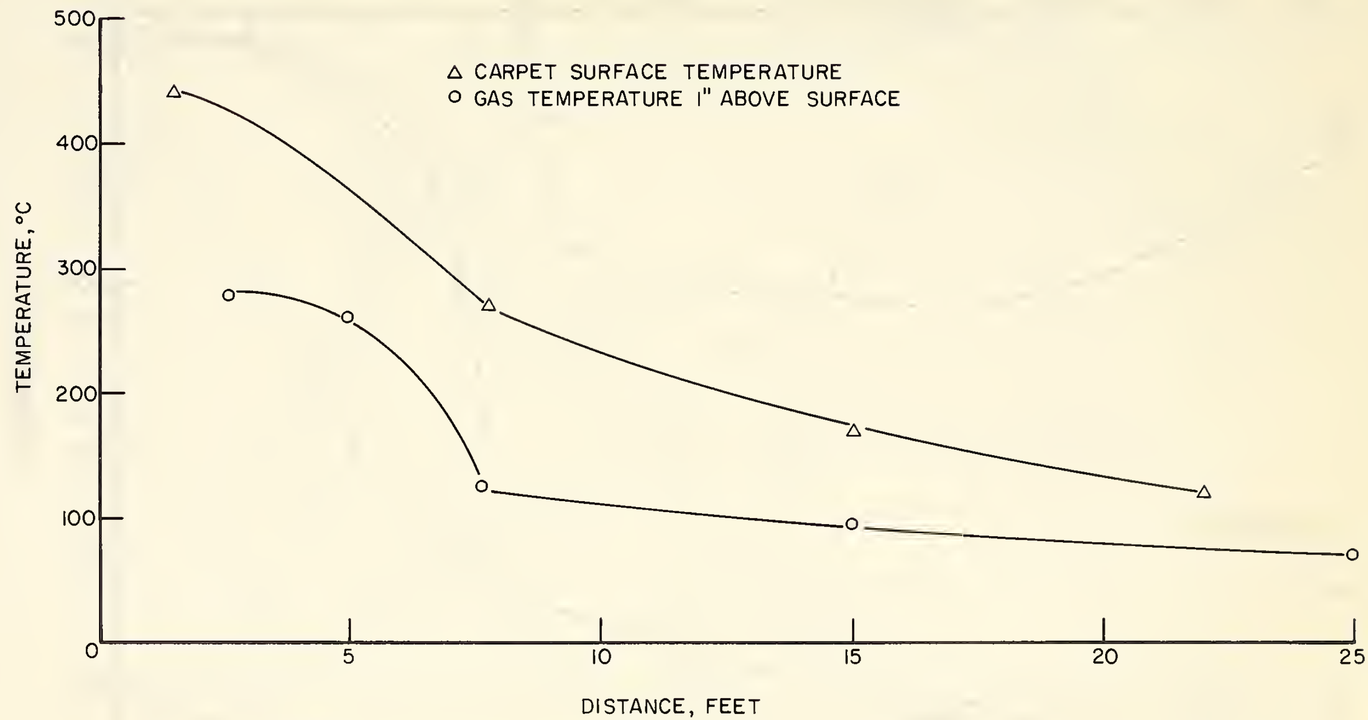

FIG. 40 CARPET SURFACE AND GAS TEMPERATURE ONE INCH ABOVE CARPET AT 6 MIN., TEST 345

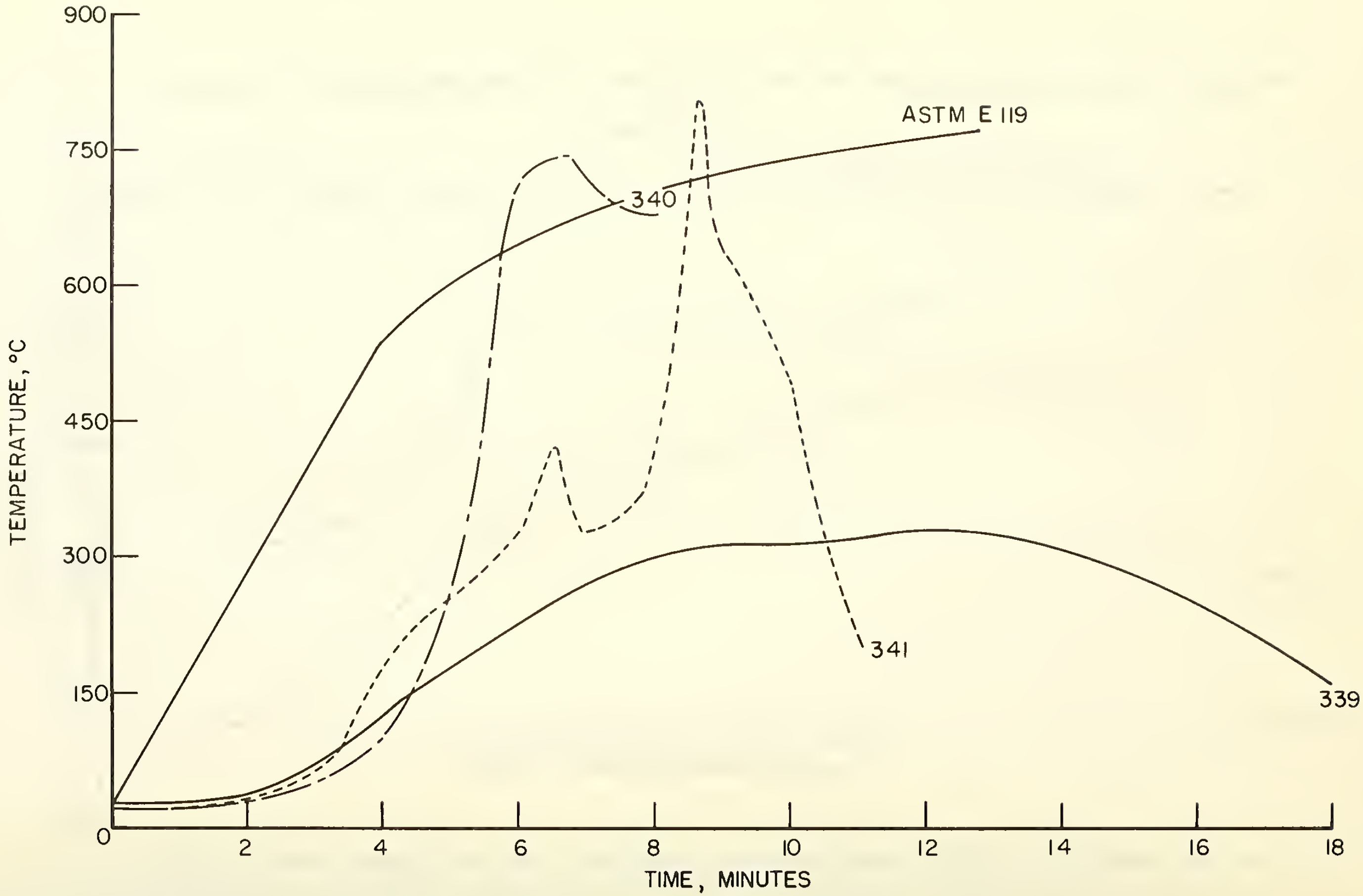

FIG. 41 CORRIDOR CEILING SURFACE TEMPERATURE HISTORY AT 10 FT. STATION

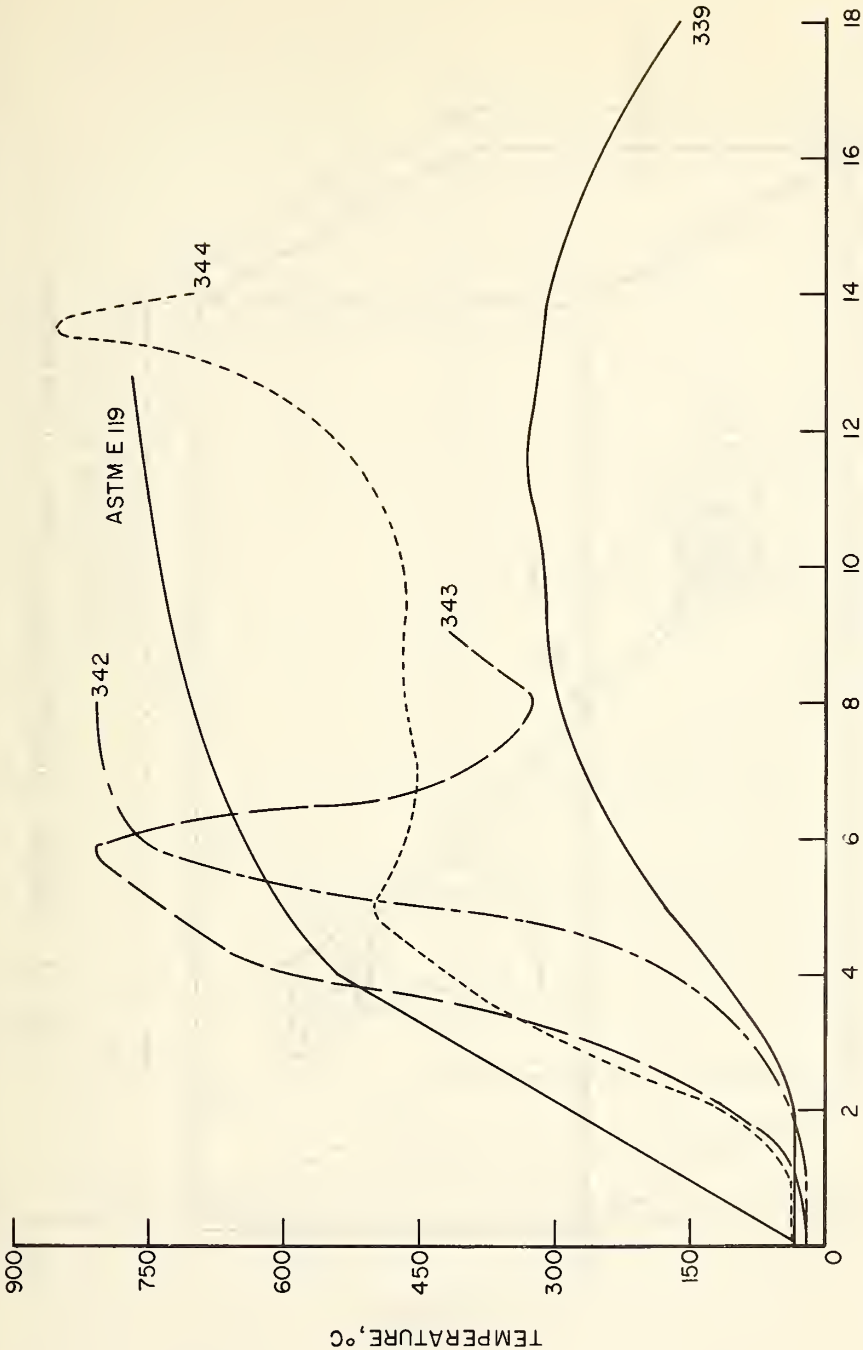

FIG. 42 CORRIDOR CEILING SURFACE TEMPERATURE HISTORY AT 10 FT. STATION

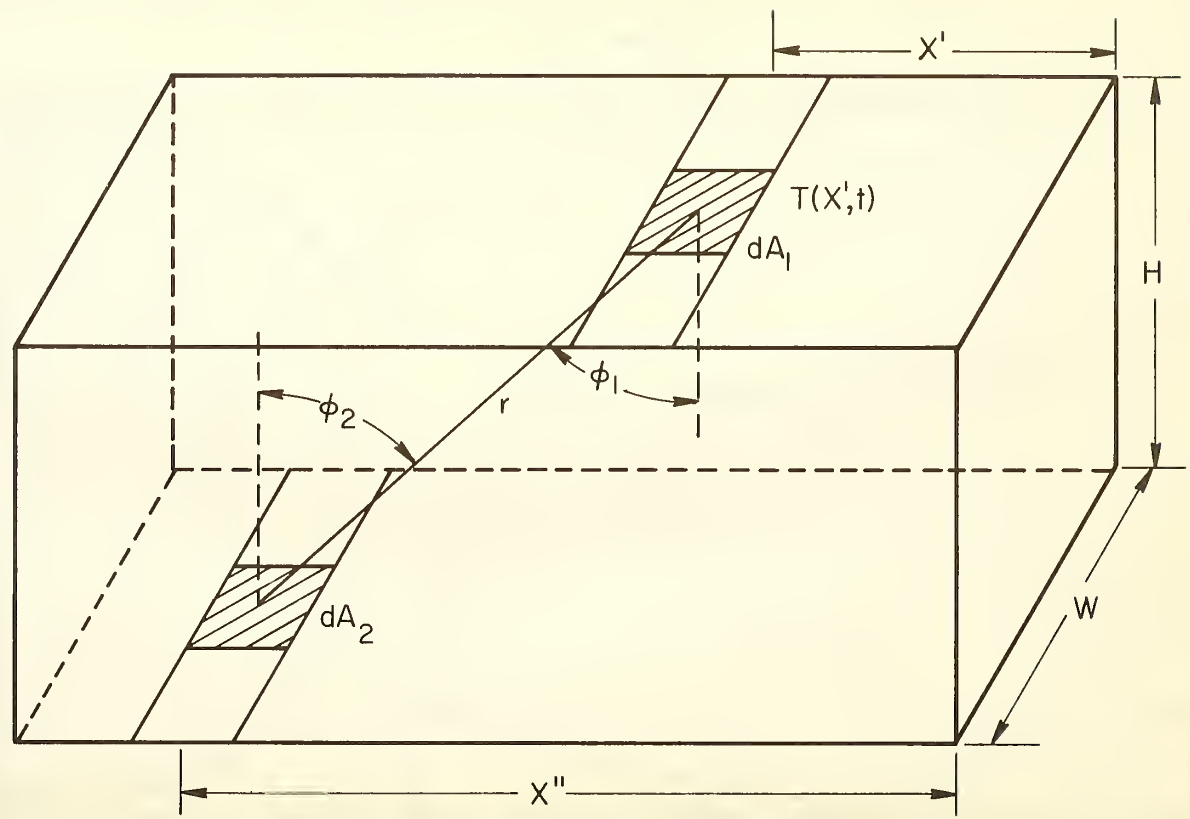

FIG. 43 CEILING RADIATION CALCULATION ILLUSTRATION

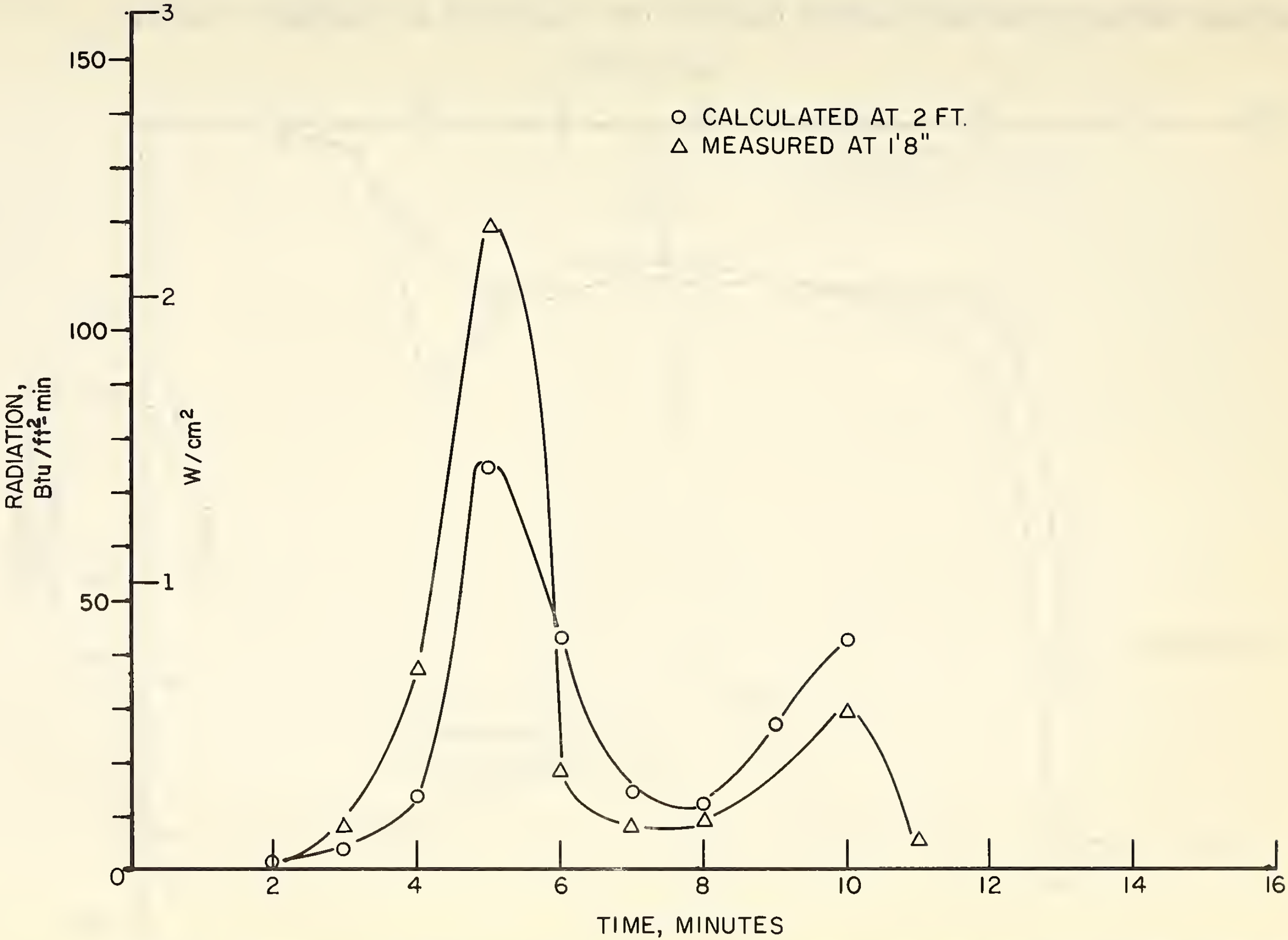

FIG. 44 COMPARISON OF CALCULATED AND MEASURED RADIATION INCIDENT ON FLOOR, TEST 343

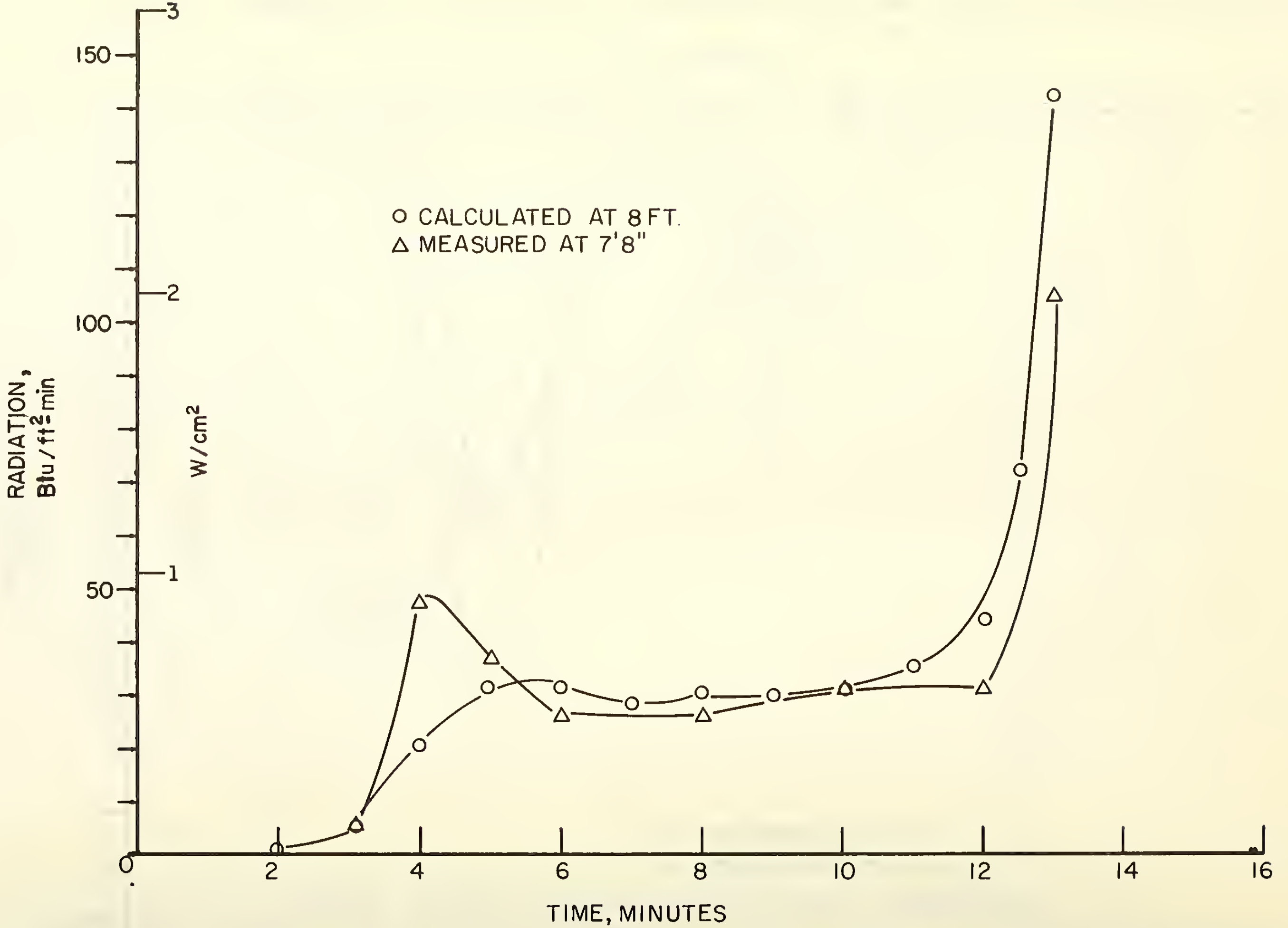

FIG. 45 COMPARISON OF CALCULATED AND MEASURED RADIATION INCIDENT ON FLOOR, TEST 344

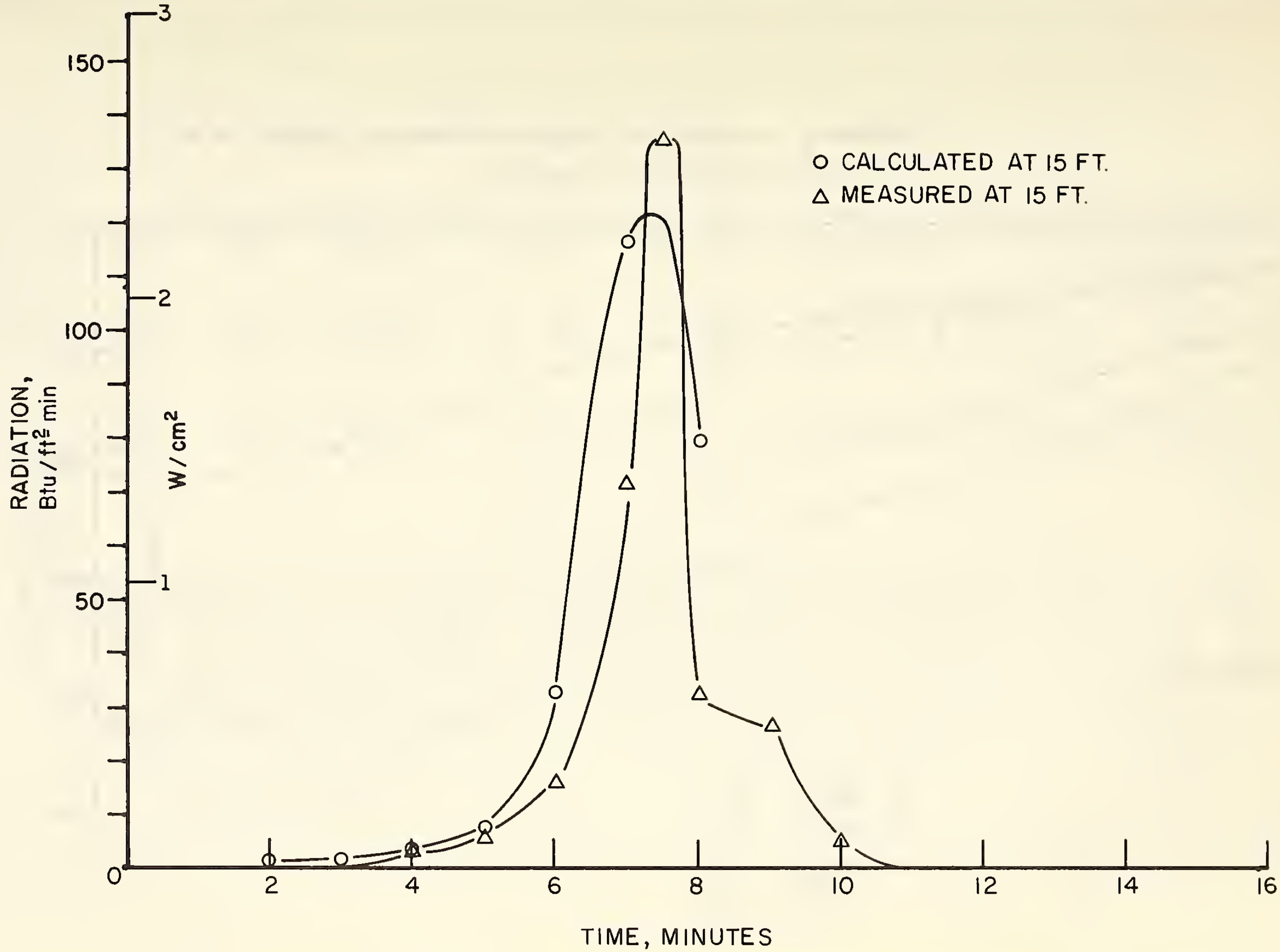

FIG. 46 COMPARISON OF CALCULATED AND MEASURED RADIATION INCIDENT ON FLOOR, TEST 345

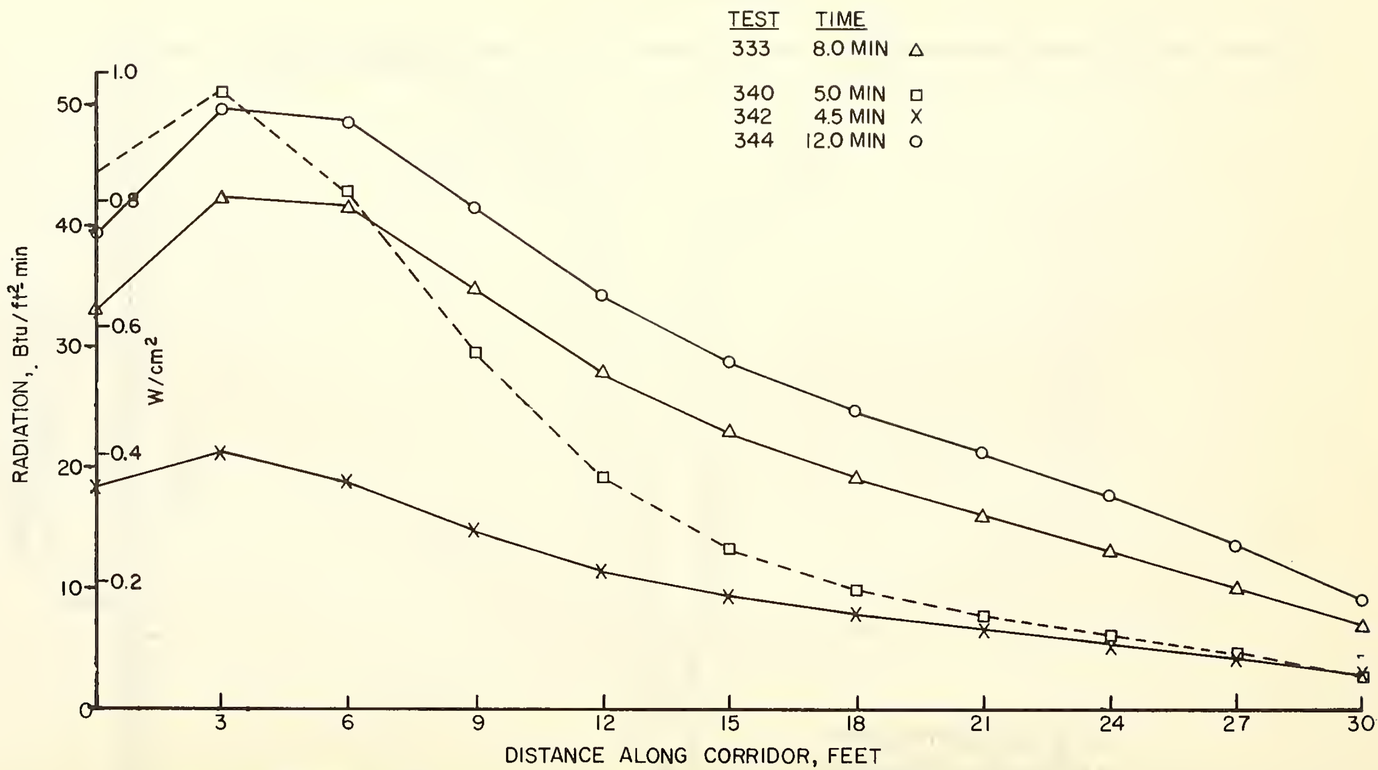

FIG. 47 INCIDENT RADIATION ON FLOOR JUST PRIOR TO FLAMEOVER

Table 1

Summary of Corridor Flame Observations

Test No.	Corridor Test Conditions				Observations	Flame* Traverse Time (min:sec)
	Ceiling	Floor	Wall	Airflow		
329	Particle board	Brick	Painted gypsum board	6200 cfm	Flame reached end of corridor along ceiling at 12:00.	***
330	Particle board	Sample No. 1 rug & pad	Painted gypsum board	0	Ceiling ignited at 2:30; carpet ignited at 2:35. Flame reached end of corridor at 2:55.	0:25
332	Particle board	8rick	Painted gypsum board	0	Ceiling flame reached end of corridor at 9:20. Carpet sample at 1'8". Station ignited at 10:15.	1:30
333	Painted gypsum board	Sample No. 1 rug & pad	Painted gypsum board	0	Flaming in corridor air at 6:00; flaming on carpet at 7:45.	
334	Particle board	Sample No. 1 rug & pad	Painted gypsum board	6550 cfm	Heavy smoke in corridor at 7:00. Flaming in corridor reached end of corridor at 9:20.	***
335	Painted gypsum board	Varnished oak	Painted gypsum board		Corridor gases ignited at 5:00; flame reached end of corridor at 8:50.	3:50
336	Painted gypsum board	Vinyl asbestos tile	Painted gypsum board	0	Flaming on floor outside burn room door at 6:30; flame on floor spread to 10 ft station at 8:40.	NA
337	Painted gypsum ooaro	Sample No. 1 rug w/o pad	Painted gypsum board	0	Carpet near burn room door ignited at 7:00. Spontaneous ignition of carpet up to 15 ft station. Fire on carpet went out at 8:00.	NA
338	Particle board	Sample No. 1 rug w/o pad	Painted gypsum board	0	Flaming in side corridor at 5:40. Flaming reached end of corridor at 7:00.	1:20
339	Painted gypsum board	8rick	Painted gypsum board	0	No fire in corridor; slight charring of gypsum paper near burn room. Air and wall temperatures reached steady state at approximately 7 minutes.	NA
340	Mineral base board	Sample No. 3 rug & pad	Mineral base board	0	Flames on carpet near burn room door at 5:00. Flame reached end of corridor at 7:05.	2:05
341	Painted gypsum board	Sample No. 10 (wool) w/ pad	Painted gypsum board	0	Flames on carpet beyond burn room door at 6:15. Carpet fire out at 7:34. Carpet reignited at 8:00. Flame reached end of corridor at 9:30.	1:30
342	Painted gypsum board	Sample No. 9 (nylon) w/ integral pad	Painted gypsum board	0	Carpet on fire at 4:45. Flaming in corridor at 4:50. Flame reached end of corridor at 6:20.	1:30
343	Painted** gypsum board	Sample No. 10 w/o pad	Painted** gypsum board	0	Carpet ignited at 4:30. Flaming on corridor floor at 5:00. Flame reached end of corridor at 5:55.	0:55
344	Painted gypsum ooard	Sample No. 12 rug, no pad	Painted gypsum board	0	5:00 gypsum board burning near burn room. 8:10 carpet burning outside burn room to a distance of 2 to 3 feet. 10:45 burning of gypsum paper oegan spreading. 12:00 flame over. 13:50 flame reached end of corridor.	1:50
345	Painted gypsum board	Sample No. 10 rug, no pad	Painted gypsum board	0	4:10 flame out of burn room. 4:25 carpet in burn room ignited. 7:00 fire in corridor air. 7:50 flame reached end of corridor.	:50

* Flame traverse time: time for flame to travel the whole length of the corridor (beginning of corridor involvement to flame reached end of corridor).

** Not fire-retardant paint.

*** Corridor flaming initiation not recorded.

TABLE 2

MATERIAL DESCRIPTION

MATERIAL	FLAME SPREAD (by ASTM E162)	DESCRIPTION
Corridor Walls		
Gypsum board	13	5/8 inch, type X gypsum wallboard, painted with intumescent white paint
Corridor Ceiling		
Gypsum board	13	5/8 inch, type X gypsum wallboard, painted with intumescent white paint
Sugar cane pulp board	74(1) 222(2)	(1) treated side (2) untreated side
Particle board	102	Pressed wood with resin
Mineral base board		Ceramic ceiling material with tunnel flame spread rating under 25
Corridor Floor		
Brick	0	Brick set in sand as basic subfloor.
Carpet No. 1 and pad	145 w/o pad 150 with pad	Brown, 100% acrylic carpet 1/4 inch low pile, 10-12 oz/sq yd. Pad,"rubberized" surfaces with jute filler 0.46 inch thick.
Carpet No. 3 and pad	445 with pad	Blue acrylic carpet 1/10-5/16 inch low pile, 32 oz-sq yd. Pad same as above.
Carpet No. 9	284 integrated pad	Gold nylon, 1/8 inch low pile, pile weight 20 oz/yd^2
Carpet No. 10	64 w/o pad 119 with pad	100% wool, 7/32 inch low pile, pile weight 38 oz/yd^2, pad same as above.
Carpet No. 12	51.3 w/o pad	Red, 100% aromatic poly-amide, 1/8" low pile, pile weight 25 oz/yd^2
Oak floor, varnished	109	Tongue-and-groove hard oak floor with two coats spar varnish, laid over 1/2 inch thick plywood.
Vinyl asbestos tile	122	Asbestos tile applied to plywood floor with black tile adhesive.
Burn Room		
Refractory coating		1/4 inch high temperature cement sprayed to basic cement block walls and cement ceiling.

TABLE 3

Smoke in Corridor Tests[1]
(Measured by Gravimetric Method at 150°C)[2]

Test No.	Time minutes	Concentration mg/ℓ
339 (BLANK)	5.0 - 6.0	0.2
	14	0.2
	19	0.1
340 (Bl. Acryl. C/P)	5.0	0.3
	7.0 - 8.0	11.5
	8.0 - 9.0	6.0
341 (Wool/P)	4.0 - 5	0.13
	9 - 9.5	1.3
	12 - 13	.07
342 (G. Nylon)	2.5 - 3	0.1
	4.2 - 4.7	0.3
	6.0 - 6.5	5.1
	8.5 - 8.9	11.2
344 (Aromatic Polyamide)	3.5 - 4.0	0.24
	7 - 9	0.13
	9 - 11.5	0.13

1. Data provided by T. G. Lee, Building Fires and Safety Section, Center for Building Technology, National Bureau of Standards.

2. Samples collected at mid-height of corridor exit window. Two parameters, the time to reach maximum smoke and the level of minimum smoke, are of interest.

TABLE 4

"FLAME OVER" INITIATION TIME

(All tests with FR painted gypsum walls and ceiling, and natural draft except as noted)

Test No.	Flooring	Time
330	No. 1 Rug and Pad (particle board ceiling)	2:35
333	No. 1 Rug and Pad	7:45
334	No. 1 Rug and Pad (particle board ceiling, 100 fpm forced draft)	7:00
335	Varnished Oak	5:00
336	Vinyl Asbestos Tiles	6:30
337	No. 1 Rug, No Pad	7:00
338	No. 1 Rug, No Pad (particle board ceiling)	5:40
340	No. 3 Rug and Pad (mineral base board walls and ceiling)	4:30
341	No. 10 Rug and Pad	8:00
342	No. 9 Rug, Integral Pad	4:45
343*	No. 10 Rug, No Pad	4:30
344	No. 12 Carpet, No Pad	12:00
345	No. 10 Rug, No Pad	7:00

*Walls and ceiling painted with white rubber base paint.

TABLE 5

Carpet Thermal Properties[1]

Carpet No.	Density lb/ft^3	Conductivity Btu/hr-ft-°F	Diffusivity ft^2/hr	Thickness inch	Pyrolysis[2] Temperature °C	Flame[3] Temperature °C
1	18.0	.054	.018	.375	300	770
3	11.5	.04	.024	.500	300	750
9	19.0	.057	.017	.390	410	820
10	17.6	.037	.009	.359	240	670
12	18.6	.045	.014	.218	320	800

1 Carpet thermal properties provided by M. R. Suchomel and T. Kashiwagi, National Bureau of Standards, 1972.

2 Temperature when pyrolysis gases are first detected in a laboratory test [8].

3 Averaged maximum gas temperature immediately above floor covering as observed in corridor during flame over.

TABLE 6

CARPET TEST COMPARISONS

a. Ranking by Corridor

Experiment Number	Flooring Material	Corridor Test Critical Cumulative Energy, Btu	ASTM E-162 Rating
340	Blue acrylic w/pad	$.65 \times 10^5$	445
342	Nylon w/integral pad	$.75 \times 10^5$	284
335	Varnished oak	1.2×10^5	109
345	Wool, no pad	1.4×10^5	64
343	Wool, no pad	1.4×10^5	64
341	Wool w/pad	1.6×10^5	119
333	Brown acrylic w/pad	2.1×10^5	145
344	Aromatic polyamide, no pad	5.4×10^5	51

b. Ranking by Rate of Heat Release

Experiment Number	Flooring Material	ASTM E-84	Heat Release Joules/cm^2*	Flammability** Test Model Critical Heat, Btu/min
333	Brown acrylic w/pad	298	8200	300
340	Blue acrylic w/pad		6493	400
342	Nylon w/integral pad	237	4901	600
343	Wool, no pad	50	3400	1250

* As determined by the NBS Rate of Heat Release Calorimeter

** Chamber type carpet flammability test developed at NBS.

TABLE 7

PERCENTAGE ERROR BETWEEN BURN TIME VALUE AND CALCULATED VALUES

Test Number	Actual Burn Time (Minutes)	Thin Bed Approximation (Minutes)	Thick Bed Approximation (Minutes)	Percentage Error (Thin Bed)	Percentage Error (Thick Bed)
333	7.75	6.55	6.33	-12.1	-15.0
337	7.0	6.23	6.15	-11.1	-12.1
340	4.5	5.28	5.43	17.2	20.6
342	4.5	5.1	4.65	13.3	3.3
344	12.00	9.45	11.6	-12.9	- 3.3
345	7.0	5.4	5.6	-22.9	-20.0

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16. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)

The NBS corridor fire program is a continuing program to investigate the growth and spread of fire and smoke through a corridor when fire is initiated in an adjoining room. Due to recent fires involving floor coverings [1], and controversies over current floor covering flammability test methods, floor coverings have received special attention during the first phase of the corridor fire program. Results of the NBS program on corridor fires are presented under the unifying concepts of energy and radiation models. The major findings are:

1. One type of carpet fire hazard has been identified as the rapid flame spread over pile surface.

2. The dominant mechanism that causes this flame spread is energy transfer from ceiling radiation. This is substantiated by measurements and calculations.

3. Carpet evaluation by critical cumulative energy input into the corridor has been found to be feasible and informative in terms of heat transfer mechanisms.

4. Finally, a radiant panel test appears to be a promising approach to simulate the corridor environment for second generation flooring tests.

17. KEY WORDS (Alphabetical order, separated by semicolons) Ceiling radiation; corridor fires; critical energy input; flame spread, calculation, and observations; floor covering evaluations; heat balances; heat transfer mechanisms; models, energy balance, radiation, and scaling.

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